

GLACIAL GEOMORPHOLOGY OF THE WEST-CENTRAL
SOUTHERN UPLANDS OF SCOTLAND,
WITH PARTICULAR REFERENCE TO
"ROGEN MORAINES"

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1979



TO MY MOTHER AND FATHER

In accordance with the University of Edinburgh postgraduate study regulation 2.4.15, the following declaration is made:

This thesis was composed by me and is based on my own research.

October 1979

In accordance with the University of Edinburgh postgraduate study regulation 2.4.11, it is recorded that part of this thesis has already been published, and a copy of the paper is enclosed at the end of the volume.

ABSTRACT

This thesis presents an interpretation of the Late Quaternary evolution of the west-central Southern Uplands of Scotland. The study area includes the Loch Doon basin and surrounding hills as well as the Carsphairn Lane - Water of Deugh - River Ken valley to the east. The study is mainly based on the results of geomorphological and sedimentological investigations of glacial deposits.

Striae, ice-moulded landforms and erratics trains from five bedrock sources were mapped and the direction of former ice movement (both during the Late-Devensian glaciation and the Loch Lomond Advance) determined. The results demonstrate a radial movement of ice (except to the east) from the Loch Doon basin during the Late-Devensian glaciation. The existence of a former ice-shed, traversing the Loch Doon basin and Carsphairn Lane - Water of Deugh valley, is also indicated. Analysis of glacial troughs and breaches showed many to be structurally controlled. The landforms of the Loch Doon basin display evidence of intense glacial erosion and glacial deposits are of restricted extent. Contrastingly, in the Carsphairn Lane - Water of Deugh - River Ken valley till deposits are extensive, even across the former ice-shed. Fluvioglacial deposits are localised, being largely confined to the NW part of the Carsphairn Lane valley. Certain of the till deposits in the Carsphairn Lane - Water of Deugh - River Ken valley form elongated ridges that are both transverse to the valley axis and the direction of former ice movement. These landforms are termed "cross-valley ridges" and form part of a genetically linked landform association: amorphous till deposits with a valley-fill morphology merge down-ice into cross-valley ridges and these are

succeeded by drumlinoids and drumlins. The cross-valley ridges appear to be related to ribbed or Rogen moraines described from Canada and Scandinavia. Analysis of the particle-size, roundness and geo-technical properties of the till and morphological associations indicate that the cross-valley ridges were deposited subglacially. It is suggested that cross-valley ridge formation was controlled by a combination of factors, the most important being ice velocity, geology, local topography and the physical properties of the till.

The limits of 11 Loch Lomond Advance glaciers are identified, all being located in the hills surrounding the Loch Doon basin. Analysis of firn line altitudes, volumes and potential snow-blowing areas of these glaciers suggests that direct insolation and transfer of snow from adjacent upland areas (especially from the SW) were important factors in controlling glacier size.

ACKNOWLEDGEMENTS

I am deeply indebted to my supervisor, Dr Brian Sissons, whose interest in all aspects of this thesis was untiring and without whose support and advice the project would not have been completed. Special thanks are also due to Don Sutherland for his valuable comments on several chapters of this thesis, and similarly to Dr Mike Walker who provided a never-ending source of encouragement.

I would particularly like to acknowledge my debt to Bill Kerr and Brian Hawkins for their invaluable and enthusiastic fieldwork assistance under what were, at times, very trying conditions.

My thanks are also due to Colin Ballentyne, Gary Cowan, Mary Dale, Dave Hodgson, Dr John Matthews, Dr Marie Robinson and Jim Rose for their help in various ways and for the many enlightening discussions over the past five years. I am also grateful to Lorna Gowans for her very competent work in photo-reducing the maps and diagrams, to Dave Agnew for laboratory assistance, to Ray Harris for drawing the diagrams and to Margaret Walker for typing the final draft of the thesis. In addition I would like to thank the farmers and the Forestry Commission for allowing me access to various parts of the study area and to Mr and Mrs D. Murdoch and Mr and Mrs D. Cameron, of Carsphairn, for their kind hospitality.

Finally, and by no means least, I wish to express my gratitude to Maree Steele who not only helped with compiling the bibliography but also provided unstinting support and encouragement over the final hurdles.

Edinburgh
October 1979.

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CHAPTER ONE

INTRODUCTION

1.1 THE AIMS OF THE STUDY

The patterns of ice movement, glacial erosion and glacial deposition in ice-sheet source areas and ice-divide zones have received little treatment by geomorphologists. There is, however, a widely held view that the constraints on glacial erosion in these areas preclude widespread glacial deposition (e.g. Flint 1971; Boulton 1975a; Gravenor 1975). Alternatively other writers (e.g. White 1972) have argued for extensive glacial erosion in these areas. It has long been known that the Loch Doon basin was a major centre of both ice accumulation and radial outflow in the western Southern Uplands during the Late-Devensian glaciation. Thus it was considered that this area might be suitable for study of the conflicting views mentioned above.

The initial purpose of this study was to investigate the relationship between ice movement, glacial erosion and glacial deposition in the Loch Doon basin and adjacent hills with a view to establishing a sequence of Late Quaternary events. However, early in the study a complex series of till ridges and associated drumlins was mapped in one of the valleys immediately east of the Loch Doon basin; the valley was also found to lie astride the former ice-divide zone. The till ridges are quite different from any other glacial landforms in the study area. Indeed, no such features have as yet been described from elsewhere in the British Isles. It was therefore decided to concentrate much of the research on these landforms.

This study thus aims to provide:

- (i) a record of ice-sheet glaciation and deglaciation of the Loch Doon basin and surrounding areas during the Late-Devensian;
- (ii) a working hypothesis for the origin of the till ridges located within part of this area; and
- (iii) a detailed map of the glaciers that existed in the area during the Loch Lomond Stadial.

1.2 THE ORGANISATION OF THE THESIS

The location of the study area and its geological and geographical components are described in Chapter 2, while the techniques employed in the research are presented in Chapter 3. The relevant literature on the glaciation and deglaciation of Scotland in general, and the Southern Uplands in particular, is discussed in Chapter 4. Chapter 5 focuses on the landforms of glacial erosion and the direction of former ice movement in the study area as a whole. Glacial troughs, breaches, rock basins and corries are described and their origins analysed, while the evidence collected from mapping five glacial erratics trains, striae and ice-moulded landforms is used to define former ice movement patterns both during the Late-Devensian and the Loch Lomond Stadial.

The landforms of glacial deposition in the Loch Doon basin and hills to the west are considered in Chapter 6 and those in the Carsphairn Lane - Water of Deugh - River Ken valley (to the east) in Chapter 7. Here, attention is focused on the morphology and distribution of the till ridges and associated landforms. This chapter also lays the foundation for the following five chapters, four of which,

particle-size analysis (Chapter 8), geotechnical properties (Chapter 9), roundness analysis (Chapter 10) and till macro-fabric analysis (Chapter 11), present the results of sedimentological investigations of the till ridges. Chapter 12 discusses the origins of the till ridges both in relation to previous work published on similar forms mapped in Canada and Scandinavia and results obtained from the present study. A working hypothesis for the mechanism of formation of these features is developed in the same chapter.

Chapter 13 details the evidence for former glaciers associated with the Loch Lomond Stadial and various palaeoclimatic inferences are made from their distribution. The thesis concludes with a synthesis of the Late Quaternary evolution of the area and suggests a number of aspects that might prove fruitful for future research in similar areas.

CHAPTER TWO

THE STUDY AREA

2.1 LOCATION

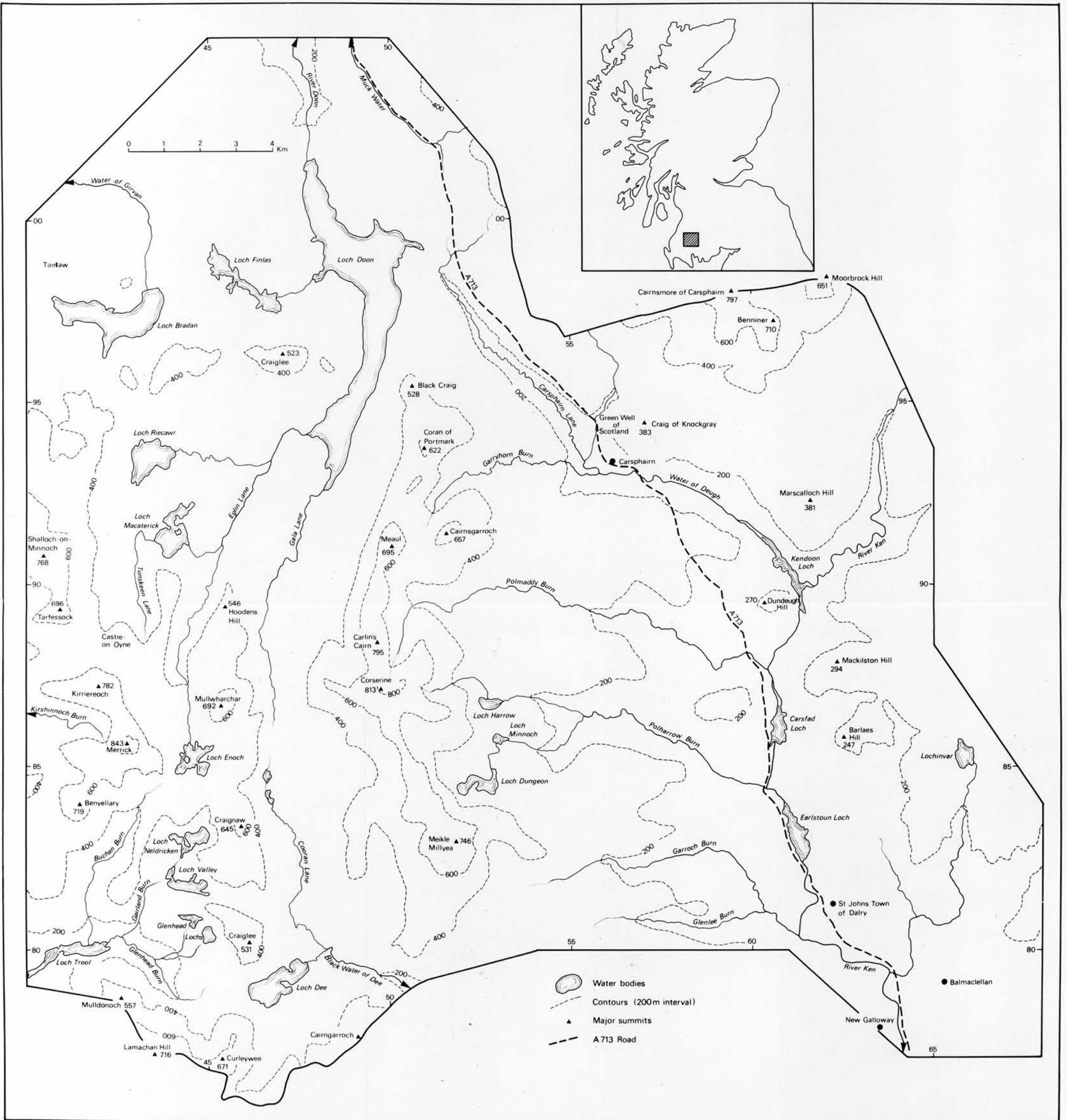
The area of investigation lies in the west-central Southern Uplands of Scotland (Figure 2.1). It is bounded in the west, arbitrarily, by National Grid easting NX 40 and in the east by a line varying between 2 and 6 km east of the A713 and B7000 roads (Dalmellington to St John's Town of Dalry). The latter boundary is delimited by the eastern extremity of a series of cross-valley ridge and drumlin landforms. The southern margin is drawn to include the hills that lie to the south of the Loch Doon granite mass and follows the line Loch Trool - Lamachan Hill - Cairngarroch - St John's Town of Dalry. The northern boundary is contiguous with the southern margin of the area mapped by Holden (1977) and extends from Tairlaw in the west to Dalmellington in the east (Figure 2.1). This region covers an area of approximately 400 km².

2.2 GEOLOGY

Although some controversy still surrounds the structure and stratigraphy of the Southern Uplands, it is possible to present a synthesis that is basically acceptable to most geologists.

It is now generally agreed that the evolution of the Caledonian Orogeny in Scotland was related to a cycle of oceanic expansion and contraction (Dewey 1969, 1971). Associated with the expansion phase Torridonian, Moinean and Dalradian sediments were deposited. The

Figures 2.1 Location and relief of the study area.

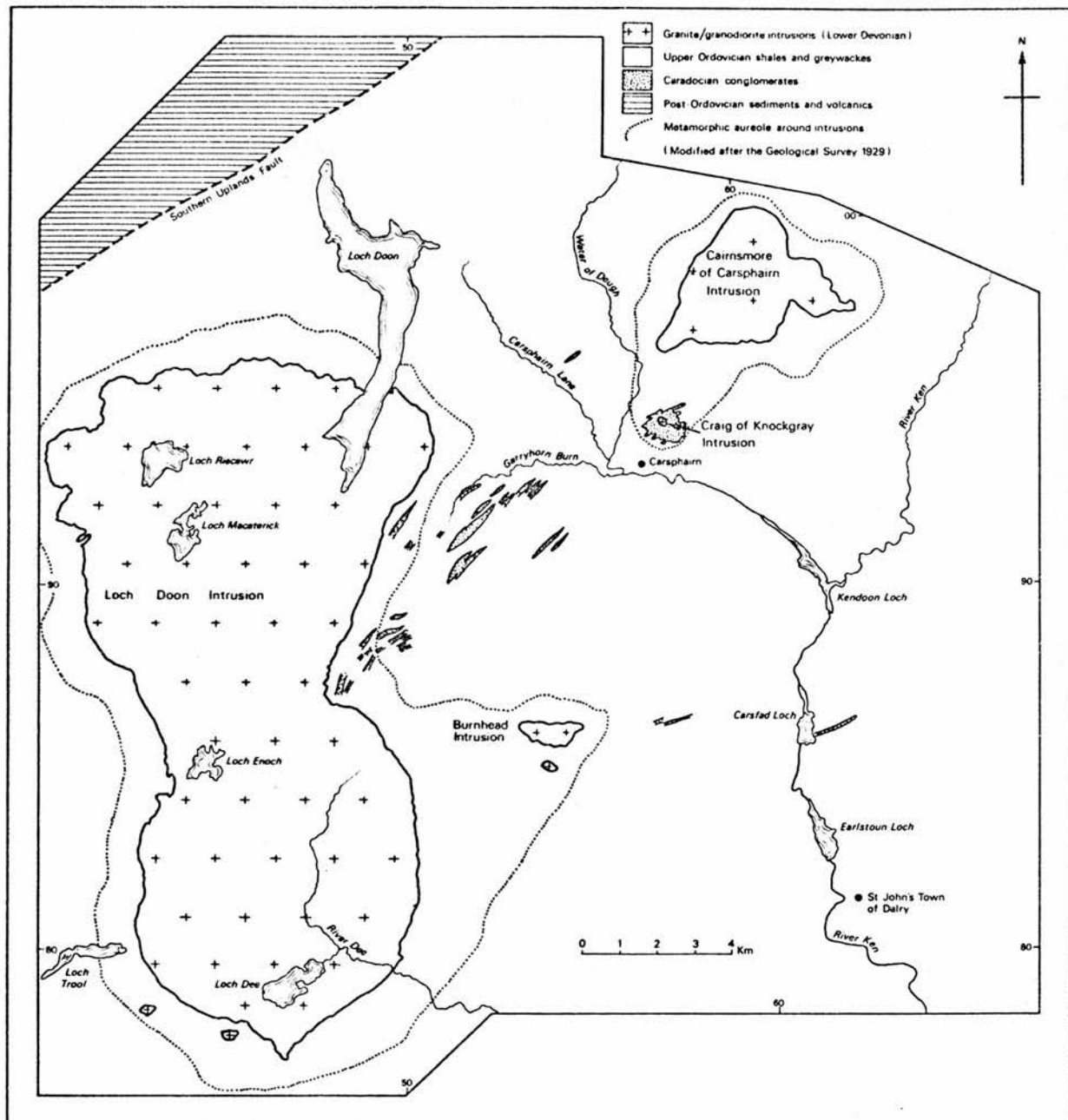


development of Benioff zones, in Late Pre-Cambrian and Cambrian times, in association with lithosphere descent, crustal consumption and deformation produced the Early Caledonian mountain chain (the ortho-tectonic zone) in NW Scotland. This sequence of events represented the beginnings of contraction of the "Proto-Atlantic Ocean". The flysh and pelagic sediments of the western and central Southern Uplands were deposited as a direct result of erosion of this mountain chain (Dewey 1971). These deposits were compressed in Late Silurian/Devonian times to form a major mountain chain known as the Late Caledonides (the paratectonic zone), the event representing the final stages of "Proto-Atlantic" contraction and rewelding of the two continental margins (Lambert and McKerrow 1976). According to Craig and Walton (1959) and Walton (1961), this phase of deformation was characterised by:

- (a) a series of large asymmetrical folds trending SW-NE,
- (b) a sequence of major strike-faults displacing the folds, and
- (c) a series of large-scale 'forceful' granitic intrusions emplaced into the sedimentary pile.

The sedimentary rocks that crop out within the study area are entirely of upper Ordovician age (Caradoc and Ashgill Series), and represent part of a thick accumulation of sediments deposited in the Caledonian geosyncline (Figure 2.2). Rutledge (1950) and Walton (1963, 1965) considered these sediments to comprise a variable suite of rocks ranging from mudstones through shales and siltstones to grits and pebbly grits that locally become conglomerates. The typical greywacke in the study area is a grey or greenish-grey rock interbedded with flaggy beds, mudstones and occasional pebbly grits. In addition the greywackes are characterised by their lack of sorting and the

Figure 2.2 Geology (solid) of the study area.



extreme angularity of their grains. While quartz is the dominant mineral particle, rock fragments are abundant in great variety, including chert, mudstone, greywacke, spilitic lava and andesite; feldspar particles are present only in subordinate amounts. These particles are embedded in a matrix that comprises a micro-crystalline aggregate of quartz, feldspar, chlorite and clay minerals. This matrix often comprises between 30 and 40 per cent of the rock by volume. The composition is extremely variable, however, owing to the differing nature of the older rocks from which they were derived.

A problem that is directly related to the mineral constituents of the till deposits analysed in this thesis concerns the origin of the greywacke matrix. Pettijohn (1975) indicated that although their origin was still uncertain, four main hypotheses may be considered:

- 1) a protomatrix - formed by trapped detrital clay;
- 2) an orthomatrix - formed by recrystallised sediment;
- 3) an epimatrix - a product of diagenetic alteration of sand-size grains; and
- 4) a pseudomatrix - the result of crushing and deformation of soft, pelitic fragments.

Further, he suggested that although each of the above were likely to have contributed to the formation of the matrix, most of the older greywackes (i.e. Palaeozoic in age) appear to have an epimatrix, which was a result of deep burial and low-grade metamorphism or high-grade diagenesis. A complication to this interpretation in the present study area is that certain of the greywackes have suffered intense thermal metamorphism through the intrusion of the Loch Doon and Cairnsmore of Caraphairn plutons. The contact metamorphism processes involved have profoundly affected the composition of the matrix of the

graywackes adjacent to the intrusion. Thus, any consideration of the characteristics of the greywacke matrix in these areas must take account of this influence.

Throughout Scotland an extensive suite of both intrusive and extrusive igneous rocks is associated with the Caledonian Orogeny. In the west-central Southern Uplands, the representatives of this suite comprise a series of late-orogenic granitic (*sensu lato*) intrusions. Two of these intrusions occur within the study area (Figure 2.2); these are the Loch Doon (also known as the Loch Dee) and the Cairnsmore of Carsphairn plutons (Gardiner and Reynolds 1932; Deer 1935).

The Loch Doon complex is a large composite intrusion that occupies an area of ca. 103 km². The major part of the pluton consists of hornblende-biotite granodiorite and biotite adamellite rocks that have a general concentric arrangement (Ruddock 1969). Hypersthene-bearing granodiorites and diorites occur in the NW and SE corners of the pluton. The rocks thus form a series that becomes progressively more acid towards the centre of the complex. The intrusion displays great structural discontinuity with the Ordovician rocks into which it is emplaced; being elongated N-S, it has caused strong deflections of the Caledonian trend (NE-SW) of the surrounding rocks. The structural trend of the pluton is further reflected in the major joint system and in the orientation of most of the minor porphyrite dykes. A satellitic granitic intrusion, which is probably a sub-surface extension of the Loch Doon mass (Parslow and Randall 1973), is exposed at Burnhead (Grid square NX 5485). As a result, in this area, the metamorphic aureole surrounding the Loch Doon pluton is 6 km wide. Elsewhere, the

aureole is generally confined in width to between 1.5 and 0.5 km from the granite-sediment contact (Figure 2.2).

The Cairnmore of Carsphairn intrusion lies 6 km NE of the margin of the Loch Doon pluton and occupies an area of approximately 15 km² (Figure 2.2). The rocks of this composite intrusion also show a concentric arrangement, increasing in acidity towards the centre. Ruddock (1969) indicated that the rocks of this pluton exhibit similar differentiation characteristics to the Loch Doon intrusion, and that the former represents the 'roof zone' of a granitic intrusion. Deer (1935) suggested that the central part of the Cairnmore of Carsphairn intrusion comprises a 'granitic rock' (although this is probably a hornblende adamellite) that consists of quartz, orthoclase, plagioclase, biotite and hornblende. This rock, according to Deer, is surrounded by a 'tonalite' (this is probably a granodiorite) comprising plagioclase feldspar with subordinate quartz and potassium feldspar and hornblende, biotite and pyroxenes as accessories. It is this latter rock that is most commonly observed as glacial erratic boulders in the Water of Deugh and River Ken valleys. In addition, a small isolated satellite intrusion, which probably belongs to the main Cairnmore pluton, crops out on the summit of the Craig of Knockgray. This inlier is of a very distinctive composition, comprising a medium to fine-grained feldspathic microgranite in which quartz is well represented, along with plagioclase, orthoclase and chloritised biotite. In general, the metamorphic aureole surrounding the Cairnmore of Carsphairn pluton is between 2.5 and 0.6 km wide.

2.3 RELIEF AND DRAINAGE

The relief of the study area largely reflects the underlying bedrock lithologies and geological structure.

The Loch Doon pluton, in contrast to the other granitic intrusions in the western Southern Uplands forms a basin that lies below the general level of the surrounding hills. Within the pluton, a prominent N-S orientated central ridge is formed by adamellite rocks. This extends from Hoodens Hill (546 m) in the north through Mullwharchar (692 m) and Caignaw (645 m) to Craiglee (531 m) in the south (Figure 2.1). West of this ridge, granodiorite forms lower ground that varies in altitude between 330 and 460 m. To the east, towering cliffs overlook an expansive area of peat bog that occupies a broad U-shaped trough extending from the shores of Loch Doon in the north to the River Dee in the south. This area lies between 220 and 300 m in altitude and corresponds in large part with the granodiorite rocks.

The Cairnmore of Carsphairn granitic pluton, in stark contrast to that of Loch Doon, forms an upstanding hill mass that culminates in a hill of the same name 797 m in altitude. The topography is much less harsh than that found on the Loch Doon pluton, generally displaying the 'rolling' landscape that is characteristic of most of the Southern Uplands.

The Ordovician strata display two distinctive relief forms:

- 1) The sediments adjacent to the two granitic plutons form a ring of high, and in places rugged, mountains whose existence reflects the superior resistance of the contact metamorphosed rocks around the granite margin (Figure 2.1). West of the Loch Doon mass the N-S orientated "Range of the Awful Hand"

culminates in Merrick (843 m), the highest point in the Southern Uplands. On the eastern side the Rhinns of Kells, again orientated N-S and exceeding 600 m in altitude for a distance of 15 km, has Corserine (813 m) as its highest summit (Figure 2.1). In the south Muldonach (557 m), Lamachan Hill (716 m), Curleywee (674 m) and Cairngarroch (557 m) rise above the granitic rocks, while the northern rim is formed of relatively low hills between 420 and 520 m in altitude. Three impressive glacial troughs breach these encircling hills: the first is in the NE corner by Loch Doon; the second at the SE corner is a steep-sided valley containing the River Dee; and the third is by Glen Trool in the SW.

The thermally metamorphosed rocks that surround the Cairnmore of Carsphairn pluton are almost as high as the adjacent granitic rocks; the two highest summits are Benniner (710 m) and Moorbrock Hill (651 m). The eastern part of this hill mass (including the granitic rocks) is cut by well-developed NNW-SSE trending U-shaped trough, which is over 250 m deep in places.

- 2) The Ordovician strata that have not undergone thermal metamorphism are largely confined to the Carsphairn Lane - Water of Deugh - River Ken valley, which lies to the east of the Rhinns of Kells range. Here the landscape is typified by a low and undulating relief that varies between 150 and 300 m in altitude. The valley itself is generally open and variable in width, which is very different from the steep, narrow valleys described by Price (1960, 1963) in the east-central Southern Uplands and contrasts with the relief developed on

the Loch Doon granite mass, where the scenery is locally almost as harsh as that of the Western Highlands.

The axis Muck Water - Carsphairn Lane - Water of Deugh - River Ken effectively forms a through valley across the eastern margin of the study area and is orientated NW-SE. Muck Water flows NW from an ill-defined watershed at 302 m (Figure 2.1), while the remaining three rivers form a major valley system trending towards the SE. Several deeply incised right bank tributary streams enter the major valley and have their sources in the Rhinns of Kells range.

The morphology of the main valley and its tributaries in this area has been modified by the deposition of till and alluvium in the valley bottoms, and the effect of this material on their cross-profile is significant. The smooth slopes of the valley sides, with bedrock near or at the surface, give way to less steep slopes towards the valley floors and in many cases the present streams have incised themselves into the valley-fill* material. Good examples of this down-cutting occur at the confluence of the Water of Deugh and River Ken and in the upper reaches of the Water of Deugh NE of the "Green Well of Scotland", where incision of up to 18 m is not uncommon. Usually in these areas the valley-fill material slopes from the valley sides towards the present stream, but generally lacks any detailed form. In certain areas, however, especially between Carsphairn and Dundough Hill, the till deposits display a ridge-like morphology orientated at

* A term adopted by Price (1983) to describe the characteristic surface expression of the till deposits that mantle most of the valley floors in the Southern Uplands.

right angles to the valley axis and the amorphous valley-fill material is largely absent. Moreover, south of Carsfad Loch the massive till deposition common farther north is generally absent and moutonnéed bedrock knobs commonly protrude through the thin drift cover. The valley at this point also takes on a glacially roughened appearance and drumlins become a feature of the landscape.

The heads of many of the tributary streams in the valley are similar to others found throughout the Southern Uplands. They are characterised by steep, smooth slopes in a semicircular arrangement and are being actively gullied by small streams. Only on a few occasions, for example by Loch Dungeon, is there evidence of over-deepening on the floors of the valley heads. Good examples of the former are found at the heads of the Garryhorn and Polmaddy Burns. Recent work on the distribution of morainic forms in this area suggests that at least some of these valley heads were the starting points of glaciers. However, there is no proof that all are the result of glacial erosion and to call them cirques would be misleading.

Most of the rivers in the study area are aligned discordantly to the geological structure and appear to show a relationship with the present distribution of high ground. This has produced an essentially radial pattern (Jardine 1959) with rivers flowing on the one hand to the Solway Firth and on the other towards the Central Lowlands. Sissons (1960, 1967a) has suggested that the divide that separates these two systems of rivers is the locus of an axis of warping from which the original drainage pattern was initiated.

The western side of the Merrick range is drained by the headwaters of the River Cree. These tributary streams are confined to

the U-shaped troughs that extend westward from the peaks of Shalloch-on-Minnoch, Tarfessock, Kirriereoch and Merrick (Figure 2.1).

Drainage is effected in the northern part of the Loch Doon granite pluton by the Eglin Lane* in the west and the Gala Lane in the east. These rivers flow ultimately into Loch Doon, and between them drain nearly two-thirds of the pluton (Figure 2.1). In their upper reaches, the streams descend rapidly by a series of waterfalls to the lower ground whence they become wide and slow-moving. The southern third of the Loch Doon pluton is drained by the Dee river system in the east and the faster-flowing Glenhead Burn - Gairland Burn system in the west. The Cooran Lane forms the headwaters of the River Dee and is typically sluggish and slow-moving, falling only 15 m in 4.5 km. In the Cooran Lane valley, a large complex of peat bogs has developed and is locally known as the "Silver Flowe" (Ratcliffe and Walker 1958; Birks 1972). A conspicuous feature of the Loch Doon basin that is closely linked with the drainage pattern is the great number of rock basin lakes. This offers a contrast to the eastern Southern Uplands, where lakes occupying rock basins have not been recorded, and is indicative of the extreme nature of the glacial erosion that the granite area has undergone.

The area to the east of the Rhinns of Kells range is drained by the Muck Water and the Carsphairn Lane - Water of Deugh - River Ken systems. Muck Water descends rapidly (falling by 130 m in 6 km) towards Dalmellington from the low and relatively open watershed, by Loch Muck, via a rugged and steep-sided gorge. The Carsphairn Lane

* The term 'lane' is a local Galloway expression and refers to a meandering stream with quiet pools and long slack stretches.

flows to the SE as a sluggish stream with a very gentle gradient (1 in 82) in a valley only 1.5 km wide. Between Carsphairn village and Dundough Hill the valley suddenly widens to almost 3 km and the Carsphairn Lane joins the rapidly-flowing Water of Deugh. Below the Dundough knickpoint, where the Water of Deugh is joined by the River Ken, the Scottish Hydro Board have constructed a series of dams and reservoirs that now regulate the flow of the water. However, the valley still maintains a gentle gradient of 1 in 56 even though it is significantly narrower (approximately 1.5 km) than farther north.

2.4 CLIMATE

The climate of the area is governed largely by the procession of cyclonic disturbances moving eastwards from the North Atlantic, which produces a mild, oceanic régime. A detailed account of the climate of the area is provided by Dight (undated), the Climatological Atlas of the British Isles (1952) and Bown (1973), and the following description is based on these publications.

The considerable variation of relief within the study area manifests itself in the diversity of climatic elements present. Thus the mean January temperature below 150 m is 6.7°C while above 670 m it falls to -0.5°C . Similarly, the mean July temperatures vary between 19°C and 10.5°C respectively. January and February are the coldest months and frost may occur on low ground from October to May.

Precipitation values are high and this falls mainly as rain. Snowfall is relatively unimportant (40 days per year at 380 m) and there are no long-lasting snow beds. At ca. 300 m, 12 to 14 per cent of the mean annual precipitation falls as snow. The mean rainfall

total on low ground is 1250 to 1500 mm, increasing to 1800 mm at 305 m, 2300 mm at 610 m and to more than 2500 mm on the summits. Owing to the rain shadow effect, however, totals are relatively low to the north and east of the main mountain masses. There is an annual average of 200 to 220 rain days (0.2 mm per rain day) and 165 to 180 wet days (1 mm per rain day) on low ground, but this frequency increases with altitude. Correlated with the high rainfall is a high incidence of cloud cover that often occurs as hill mist, low cloud covering the summits on average 200 days per year.

2.5 SOILS

Over most of the study area the land surface consists of soil-forming materials rather than soil proper. The high precipitation over much of the region results in extensive leaching, and there is also a great deal of impeded drainage (Birke 1969; Bown 1973). Under these conditions, the dominant soil-forming process is either podzolisation or gleying.

In general, the upland valleys show a catena with a sequence of soil types related to slope and soil moisture status. Blanket peats, gleys and podzols occur on the lower and middle slopes, while skeletal mineral soils and patterned mountain tundra soils occupy the upper slopes and summit areas (Bown 1973).

In the lowlands, soils that exhibit regular profiles are normally found. Owing to the extensive occurrence of till, most of the soils are gleys of various types, but occasionally podzols occur. On the flatter areas bordering some of the rivers alluvial and meadow soils are present.

Overall, the acid rocks of the west-central Southern Uplands give rise to soils with a low nutrient content, so that soils with a fertility of agricultural standards are distinctly localised. As a result, in many areas, the soils with low agricultural potential are being planted with coniferous forest (see below).

2.6 VEGETATION

The most comprehensive works on the present vegetation of Scotland are those by McVean and Ratcliffe (1962) and Burnett (1964), and the following description is based on these publications.

The study area falls within the 'oak forest with birch' region, although only a few relics of semi-natural woodland survive, notably the Wood of Cree (near Newton Stewart, National Grid Reference NX 3871), the wood by Glenlee (near New Galloway, NX 6080) and the Caldots, Buchan and Glenhead Woods in Glen Trool (NX 398787; NX 417802; NX 428803). These woods are principally *Quercus petraea* (sessile oak) with *Betula pubescens* (birch), *Ilex aquifolium* (holly) and *Sorbus aucuparia* (rowan) in association.

The vegetational assemblage below 450 m is that characteristic of western blanket bog. *Sphagnum-Eriophorum* bog occupies large areas of flatter, poorly-drained ground, while *Molinia caerulea* (purple moor grass) and *Myrica gale* (bog myrtle) are found where there is significant water movement. On steeper slopes the peat is shallower and *Calluna-Tricophorum* bog dominates. Burning, however, has affected these communities and promoted the growth of *Molinia caerulea* at the expense of *Calluna vulgaris* (heather). Above 450 m on well-drained slopes *Agrostis-Festuca* grassland becomes prominent, with *Nardus*

becoming locally dominant.

At the present time, the wild and desolate nature of the area is being rapidly altered. The Forestry Commission, along with two other private forestry concerns, have taken over large parts of the region in order to plant extensive stands of coniferous woodland. *Picea sitchensis* (sitka spruce) is being used widely in reafforestation, along with *Picea abies* (Norway spruce), *Larix leptolepis* (Japanese larch) and *Larix x eurolepis* (hybrid larch).

CHAPTER THREE

RESEARCH METHODS

3.1 INTRODUCTION

This chapter deals with the field and laboratory methods used in the pursuit of the study objectives outlined in Chapter 1. The spring and summer months of 1974 and 1975 were spent in the field and the laboratory programme completed during the autumn months of 1974 and 1975.

3.2 FIELD TECHNIQUES EMPLOYED IN THE WHOLE STUDY AREA

The whole area was first studied on vertical aerial photographs at a scale of 1:25,000, using an Old Delft scanning stereoscope. All identifiable glacial features and drift boundaries were marked on the photographs. These were used as a base for field mapping, which was carried out on transparent overlays. Subsequently, the completed field maps were transferred to Ordnance Survey 1:10,560 or 1:25,000 scale sheets. Where adequate ground control was available this was done by eye, but otherwise use was made of a Zeiss Sketchmaster, various precautions being taken to reduce the effects of displacement in the photographs.

In addition, to assist in the elucidation of the principal directions of former ice movement, detailed mapping of glacial erratic boulder trains, striae and ice-moulded landforms was carried out over the whole of the study area. The techniques used were as follows.

(1) Glacial erratic boulder trains

Boulders derived from five source rocks within the study area were mapped in order to determine former directions of ice flow. This method has been successfully used by other workers in the Southern Uplands, for example by Skae et al. (1877) and Charlesworth (1926a) on the Loch Doon and Cairnsmore of Carsphairn granite erratics and by McCall and Goodlet (1952) on the Tinto Hill felsite.

A complication occurs, however, in that this area, in common with the rest of Scotland, has been covered by ice on a number of occasions. Hence some of the erratics may have reached their present resting places by devious routes, having been transported in different directions by the glaciers at different times. As there is no way of assessing the effect of previous glaciations on the deposition of erratics, it is assumed that the boulders mapped correspond to the final movements of the Late-Devensian ice-sheet or, as with one erratics train, the glaciers formed during the Loch Lomond Stadial. Further, Charlesworth (1957) has indicated that erroneous conclusions may be reached in mapping erratics because they may be derived from older conglomerates, remanent deposits from previous glaciations, pre-glacial streams, unrecorded outcrops of the rocks concerned or outcrops that may have been completely removed by glacial erosion. In order to increase the reliability of the mapping, every effort was made to reduce the possibilities of errors arising from extraneous factors. This was done by limiting the use of erratics to those cases in which a clear regional trend could be demonstrated. Such a trend of a particular erratic should approximate to a negative exponential function (Krumbein 1937) and as such would indicate the source area and

therefore rule out the possibility of errors of the type described above.

The source rocks used and erratics trains mapped in this study were:

- (a) boulders of the Loch Doon and Cairnsmore of Carsphairn granite where they rested on the surrounding Ordovician strata,
- (b) boulders of Caradocian conglomerate resting on Ordovician greywacke bedrock,
- (c) boulders of Ordovician greywackes and shales lying on the Loch Doon granite, and
- (d) boulders of the Craig of Knockgray microgranite where they rested on Ordovician rocks.

Traverses at ca. 500 m intervals, covering the ground adjacent to the source rock exposures, were walked systematically and the location of erratics marked on 1:25,000 Ordnance Survey sheets. At the 'feather edge' of each train, the traverse interval was reduced in order to gain a more detailed picture of the margin.

In certain areas (for example, by the village of Carsphairn) the presence of numerous stone walls provided a useful adjunct to the traverse mapping. The technique of mapping specific rock types that occur in stone walls has been used by geologists prospecting for mineral deposits in areas of limited bedrock exposure (Cazalet 1973; Morrissey and Romer 1973) as well as by geomorphologists for elucidating dispersal patterns of debris by ice (Shakesby 1978a, b). Within the study area the procedure adopted involved the inspection of each metre length of wall, the observed erratics being marked on

either the 1:25,000 or 1:10,560 scale Ordnance Survey maps. In using this method it has to be assumed that the walls have been constructed of boulders removed from adjacent fields and thus have not been carried far by human agencies. Consistent results obtained over wide areas suggest that this assumption is valid.

(ii) Glacial striae

Striae are by no means abundant in the area and this is particularly so on the exposures of granite. By contrast the metamorphosed Ordovician strata display well developed striae, especially on surfaces recently exposed by Forestry Commission road and quarry excavations.

Initially, evidence of striae was extracted from sheets 8, 9 and 14 of the 1:63,360 sheets of the Institute of Geological Sciences, and where possible these were later checked in the field using a Suunto compass-clinometer. The orientations of any additional striae were measured and added to the map. The method adopted here was to take several measurements of the orientation of the striae present on a rock surface and then to plot the mean of the results.

(iii) Ice-moulded landforms

All drumlin, crag-and-tail and roche moutonnée features were mapped on 1:25,000 scale Ordnance Survey sheets in order to provide supplementary information on the direction of ice movement. Different symbols were used in the field mapping to distinguish between each type of ice-moulded landform.

As the northern margin of the Galloway drumlin field was included within the study area, mapping of the outlines and crest positions of these landforms was undertaken. Only the major crest

alignments were mapped as large-scale mapping of every ridge and mound occurring on each drumlin was found to obscure the overall trend. Where crag-and-tail, roche moutonnée or rock drumlins were encountered, the outline alone was mapped and any striae measured and superimposed.

3.3 FIELD TECHNIQUES EMPLOYED IN THE EXAMINATION OF THE CROSS-VALLEY RIDGES

(1) Morphological mapping

During the course of the fieldwork, a series of unusual ridge-like landforms, orientated normal to the valley axis and composed entirely of till, was discovered in the Carsphairn Lane, Water of Deugh and River Ken valleys. Due to the very intricate nature of these features, it was decided to map them in detail at 1:10560 scale. Aerial photographs of this particular area at 1:10560 scale were not available; therefore the procedure adopted was to transfer the outlines and crests of the larger ridges from the aerial photographs, which had already been mapped at 1:25,000 scale, onto 1:10560 Ordnance Survey sheets using a Zeiss Sketchmaster. These outlines and crests provided the base map upon which the more detailed mapping was based. The 1:10560 sheets were then taken into the field along with the aerial photographs and the remaining ridges and mounds carefully located on them. Particular care was taken to plot the outline and crest of each ridge, mound and hummock. Finally, the aerial photographs were compared with the completed 1:10560 scale maps (again using the Sketchmaster) in order to check for possible errors in the location of the smaller ridges and mounds. Although mapping on this scale

proved to be very time consuming, taking over six weeks to map the features completely, it was felt that the unique nature of the landforms warranted this detailed attention.

Several other problems were encountered while this work was being carried out. In certain areas of the valley, for example by Marscalloch Farm and Dundough Hill, extensive thirty-year-old conifer plantations occur. The thick and impenetrable nature of these areas made the mapping of any contained landforms virtually impossible. Secondly, although numerous excellent roadside and river bank sections revealed the composition of the majority of the cross-valley ridges, good sections were not present over the whole area. Clearly, the digging of pits in every ridge and mound to determine its composition was an impracticable exercise. Thus, where several ridges of similar morphology were found in juxtaposition, but with only one exposure present, it was assumed that the other ridges were composed of like material. Finally, in the inter-ridge hollows extensive peat deposits had accumulated, possibly concealing ridges beneath, making the mapping of these areas difficult.

Results obtained from the mapping of glacial erratics and striae in the area indicated that the ridges were orientated transverse to the former direction of ice movement. The ridges also appeared to be related to eskers, drumlins and valley-fill deposits in the same valley. Moreover, several sections revealed the presence of two tills, an upper olive-coloured unit and a lower grey unit.

Interpretation of these landforms using only the mapping procedures outlined above proved impracticable and therefore recourse was made to more quantitative methods in order to obtain additional

information. Thus at every exposure within the cross-valley ridges a description of the stratigraphy, depth of weathering, stoniness, erratic content and colour (using Munsell Colour Charts) was made. Till macro-fabric analysis, roundness analysis of the contained clasts and the collection of bulk samples were carried out at selected sites, and a detailed survey programme undertaken to provide information on the surface and buried expression of some of the ridges. The techniques employed are described below.

(ii) Till macro-fabric analysis

A random sampling design was not employed in selecting the sections at which the till fabrics were sampled. In many parts of the area exposures suitable for fabric analysis were so rare as to make random sampling impracticable. However, modifications to the A713 road between Dalmellington and St John's Town of Dalry had exposed a number of fresh road-cuts in the cross-valley ridges and thus it was possible to carry out a till fabric programme at numerous ridges. Three fabrics were sampled from each ridge according to a predetermined design; one fabric being sampled from each limb of the ridge and one from the core. Where complete roadside sections through the ridges were not available, individual fabric analyses were completed wherever appropriate sections occurred.

Each fabric analysis was carried out by first cutting a horizontal platform (approximately 60 x 60 cm) in the till, at least 1.5 m below the ground surface in order to minimise the effects of disturbance of the fabric by post-depositional processes (Beaumont 1971a). Many workers have preferred to measure stones from a cleaned vertical face, but this approach can lead to a sampling bias as

"there is a great temptation when sampling a vertical face to select pebbles that are projecting out of the face" (Andrews 1971a, p.11). Further, investigations by Kauranne (1960), Andrews and Shimizu (1966), Johansson (1968), Young (1969) and Boulton (1971) have shown that fabrics can change rapidly, particularly in the vertical plane, in a till sheet. The "platform" method was therefore adjudged more appropriate, especially as the vertical depth from which the stones were sampled was usually less than 8 cm. Pebbles not less than 1 cm long and with a length to width ratio greater than 3:2 were excavated from this surface (cf. Kirby 1969; Krüger 1970; Evenson 1971).

A Suunto compass-clinometer was used to measure the long axis orientation and dip of each pebble to the nearest 5° . No restrictions were placed on the dip of the long axis of pebbles. It is essential not to exclude stones with steep dips as these may be of diagnostic significance in analysing the processes of till deposition or subsequent modification of the fabric. Some workers have chosen to reject pebbles with dips exceeding 60° (e.g. Kirby 1969; Young 1969), while others have preferred different limits of, for example, 70° (e.g. Hill 1971), 40° (e.g. Krüger 1970) and 30° (e.g. Johansson 1968). Krüger (1973) in a laboratory experiment found that accurate measurement of particles with a dip exceeding 50° was difficult. In practice, however, it was found that the dip of pebbles sampled rarely exceeded 45° .

Discoidal and rounded pebbles were rejected from the analysis as it was impossible to determine the preferred orientation of these stones. Pebbles touching one another were also rejected, as were particles from the matrix around large boulders in the till, for the matrix here can show sympathetic flow structure around the boulder

(Miller 1884).

The problem of sample size for fabric studies has been discussed by several workers. Harrison (1957a) suggested that a sample size of 25 pebbles was sufficient, whereas Krumbein and Pettijohn (1938) maintained that at least 100 stones should be measured. Harris (1969) and Young (1969), however, have shown that there is no significant difference between fabrics derived from samples of 50 and 100 pebbles. Hence, a sample size of 50 was considered adequate for the present study.

A total of 41 till fabrics was sampled and the values for orientation and dip recorded for each particle on a prepared form. These were subsequently plotted onto a conventional polar equidistant projection, allowing 10^0 for each orientation measurement as a correction for magnetic variation west of true north. This procedure ensures greater objectivity of particle selection and is preferable to either direct plotting on a polar net (Harrison 1957a) or use of a till fabric rack (MacClintock 1959).

The results were initially analysed using a variety of conventional two- and three-dimensional statistical techniques. These, however, were found to be inappropriate for the analysis of bimodal and multimodal fabrics, a feature that characterised many of the fabrics measured from the study area. Thus an alternative analytical procedure was adopted and this is discussed in some detail in Chapter 11.

(iii) Roundness analysis

It has been suggested that differentiation of tills may be assisted by measuring the roundness characteristics of the included

clasts (e.g. Dreimanis and Reavely 1953; Drake 1971; Flint 1971). The measurement of stone roundness, however, has for long remained the subject of much debate. Many workers have considered roundness to be independent of shape (Wadell 1932; Krumbein 1941a; Powers 1953; Van Andel *et al.* 1954; Curray and Griffiths 1955; Fleming 1965; Whalley 1972). Alternatively Schwartz and Shore (1966) considered roundness dependent on sphericity, while Russell and Taylor (1937) suggested that the two were interdependent. Ehrlich and Weinberg (1970) have criticised this approach, suggesting that shape characteristics should be thought of as operating over a continuum. For the purposes of this study it was found most logical to follow Fleming (1965, p.385) in defining roundness as "a dimensionless function of curvature of one or more corners".

A great deal of discussion has also centred on the methods employed in the determination of stone roundness. All approaches to this problem seem to possess certain disadvantages, and as Whalley (1972, p.962) has pointed out "... there is no satisfactory and objective method for defining roundness and no practical way of measuring it".

Two major approaches to the measurement of stone roundness have been made by geologists and geomorphologists:-

1) Techniques involving the direct measurement of clasts.

Wadell (1932) expressed roundness as the ratio of mean roundness of curvature of the corners to the radius of the inscribed circle. A second method has been presented by Cailleux (1945), which is essentially the same as that produced by Wentworth (1922a), where the radius of curvature of the sharpest corner of the clast in the maximum projection plane

is determined (see King (1966) for a useful summary of this technique). This latter procedure has been used by numerous workers (e.g. Tricart and Schaeffer 1950; Nossin 1959; Blenk 1960; Cailleux and Tricart 1963; King and Buckley 1968; McCann and Owens 1969; Hollerman 1971; Dugdale 1972; Gregory and Cullingford 1974; Rose 1975).

This method does, however, possess four main drawbacks.

- (i) With decreasing size and roundness the accuracy of the technique diminishes (Van Andel *et al.* 1954; Whalley 1972).
- (ii) Difficulty can result from estimating the radius of curvature using a template of concentric circles, especially where boulder-size clasts are being measured.
- (iii) Not all workers select the same corner to measure (Folk 1972).
- (iv) The measurement of pebbles less than 1 cm in diameter is virtually impossible.

- 2) Visual comparison charts, which comprise a series of silhouettes or photographs showing varying degrees of particle roundness, have found favour with many workers and numerous roundness classifications based on this technique have been proposed (e.g. Trowbridge and Mortimore 1925; Russell and Taylor 1937; Krumbein 1941a; Powers 1953; Reichelt 1961; Lees 1964). The classifications developed by Krumbein (1941a) and Powers (1953) have been employed most frequently by geomorphologists studying till deposits (e.g. Andrews 1963b; Drake 1971, 1972; Reheis 1975; Mills 1977a; Boulton 1978).

This approach has been criticised for its susceptibility

to operator bias (Trowbridge and Mortimore 1925; Rosenfeld and Griffiths 1953; Griffiths 1967; Folk 1972; Whalley 1972), not only in selecting the class division (Russell and Taylor 1937), but also because there is a "psychological tendency to make the data fit theoretical predictions" (Sneed and Folk 1958, p.117).

It was decided to employ the chart comparison method for the analysis of the clasts in this study as it was considered to be the most practical in terms of rapidity of measurement and ease of use in the field. Moreover, as two different clast size ranges were to be studied, the second of which was at microscopic level (see p. 35), then the use of the comparison chart was further vindicated owing to the difficulty encountered in obtaining the radius of curvature measurement on small particles. The use of the same technique on both size ranges would also enable direct comparisons to be made between the two. In an attempt to reduce the degree of subjectivity inherent in this method, two operators were used at all times during measurement of the larger size particles. Consistent results obtained over most of the analyses suggest that the operator bias was reduced to an acceptable level.

At 42 sites 100 clasts between -4 and $-8 \phi^*$ diameter (16-256 mm) were examined as they were removed for till fabric analysis. Any additional stones required for the analysis were excavated from the section after the till fabric measurements had been completed. The

* Φ (ϕ) represents particle-size expressed as $-\log_2$ of the particle diameter in millimetres (Krumbein 1934).

clasts were classified as either well-rounded, rounded, sub-rounded, sub-angular, angular or very angular according to the notation developed by Powers (1953). A modified version of the Powers visual comparison chart, formulated by Folk (1955) to aid statistical analysis of the results, was used in the field, the chart being photographically enlarged to facilitate accurate matching. The results were later plotted onto a ternary diagram and various statistical techniques employed to analyse them.

(iv) Bulk sampling

Sixty-four bulk samples of till and one of sand and gravel, weighing 1-2 kg each, were collected and removed to the laboratory where particle-size analysis, roundness analysis, lithological analysis, carbonate content and flow limit tests were conducted to assist in differentiating the tills. These techniques are described in section 3.4.

(v) The survey programme

A detailed survey programme was carried out on the cross-valley ridges in the area where they were best developed. This work had the following objectives:

- (a) to determine the sub-peat profile of the inter-ridge areas and to ascertain whether or not buried ridges are present; and
- (b) to obtain information on the slope angles and spacing of the ridges.

For the purposes of this work, a Wild D.I.3. "Distomat" was employed. This instrument is an electronic reducing tachaeometer, which uses an infra-red light beam emitted from a GaAs diode housed in an aiming head.

The aiming head is mounted on a Wild T¹A Double Centre Theodolite and both are linked to a computerised control unit below. A single prism reflector (GDR 31) is used to return the infra-red beam to the instrument, giving it a range of 400 m and an accuracy of ± 5 mm. The control unit first calculates the sloping distance between reflector and instrument. After the vertical angle is read off and punched in, the horizontal distance and difference in height are calculated. The complete system is powered by a rechargeable 12 volt NiCd battery, which is sufficient for 500 distance measurements.

Mr B Hawkins, graduate student, Geography Department, University of Edinburgh, acted as instrument operator for the survey programme, while the writer operated the reflector. The programme took 28 days to complete and was carried out during the summer of 1975.

A series of traverses was surveyed across the ridges located SE of Carsphairn and in the Garryhorn valley. The traverses were spaced laterally at ca. 50 m intervals to obtain a detailed picture of the variation in ridge morphology upslope. Linearity of the traverses was maintained by placing ranging rods at one end of a traverse and aligning the reflector pole with them. The spacing of individual points on each traverse was governed largely by the changes in ridge morphology, but normally points were more closely spaced (2-3 m apart) across ridge crests and inter-ridge hollows. Inevitably, areas of "dead ground" were encountered on certain traverses. This problem was overcome by supporting the reflector pole on steel rods that were held on the ground surface. All traverses were tied to Ordnance Survey bench marks and closing errors were less than ± 0.05 m.

The altitude of the sub-peat surface was found by pushing steel rods (from a small Hiller borer) through the peat and allowing for the depth in subsequent calculations. The actual point of measurement was adopted after first making several probes to ensure that the point chosen was representative. This technique proved important as in places peat depths in excess of 7 m were discovered in the inter-ridge hollows.

3.4 LABORATORY ANALYSIS

The bulk samples collected from the cross-valley ridges were analysed using the following techniques.

(1) Particle-size analysis

Particle-size analysis has proved to be a useful method for differentiating tills (e.g. Krumbein 1933, Dreimanis and Reavely 1953, Shepps 1953, Arneman and Wright 1959, Kaiser 1962, Drake 1971, Johnson *et al.* 1971, Mulholland 1976, Mills 1977a, c, Vorren 1977, Madgett and Catt 1978). Despite the uniform bedrock lithology in the Carsphairn Lane - Water of Deugh valley, field observation indicated that it might be possible to distinguish between the two tills exposed in the above area on the basis of their particle-size characteristics.

Although the technique has been used extensively by geomorphologists, any results obtained should be viewed in the light of certain variables that may affect the analysis.

- 1) As the particle-size characteristics of a till are partly the result of both the regimen of the glacier and the bedrock

over which the ice moved, sand, silt and clay percentages do not necessarily provide an infallible identification of any individual till. Rather, the technique should be viewed as only one of the many properties that can be used to categorise the deposits (Dreimanis and Reavely 1953; Frye *et al.* 1969).

- 2) An important restriction on particle-size studies is the alteration of the original size distribution by post-depositional agencies such as diagenesis and leaching.
- 3) The clay-size fraction of the till is determined by methods based on differential settling velocities. These velocities are notably affected by the shape and specific gravity of the particles as well as by their size. Analytical results may therefore be misleading in that the size values computed from fall velocities are based on the premise that the particles are spheres of quartz (Krumbein and Pettijohn 1938).
- 4) Comparison of results from any one study with those of other workers is a difficult process and one that should be avoided, owing to the different analytical procedures used and the varying size ranges analysed.

Particle-size analysis on the matrix ($<0.0 \phi$ diameter) of the grey and olive tills, using the sieve and pipette method, was carried out on all 64 samples collected in the field (Folk 1968, pp.33-39). The pipette method was used since it was considered to be the most accurate (Folk 1968). Each sample was air-dried and worked by hand through a 2 mm (0.0ϕ) sieve. Any coating of silt or clay adhering to the pebbles was scraped off and also worked through the sieve.

The material passing through the 2 mm sieve was repeatedly split

using the coning and quartering technique until the sample size was reduced to 100-150 gm. Organic matter was removed by pretreatment with a 20% solution of hydrogen peroxide. Sodium hexametaphosphate (Calgon) was used as a dispersing agent. The relative proportions of material at 0, +1, +2, +3, +4, +5, +6, +7, +8 and +9 ϕ , covering the range from very coarse sand to clay, was determined by this method for all the till samples collected.

Each sieved fraction was weighed to 0.001 gm. Such accuracy is necessary when probability paper is used in the plotting of the results, as the "tails" of the distribution are expanded. After weighing, each fraction was examined under a binocular microscope and the percentage of aggregates, if any were present, deducted from the raw weight. If the fraction contained over 20 per cent aggregates the crushing and sieving process was repeated. Folk (1968) has emphasised the importance of this procedure in that if the aggregate percentages are ignored sensitive measures (such as skewness and kurtosis), which reflect the normality of the distribution, may be distorted and spurious results calculated. The critical nature of this approach was demonstrated by the presence of 15-20 per cent of aggregates in certain grey till samples.

The corrected weights were first cumulated, the cumulative percentages derived and these plotted against phi diameter on arithmetic probability paper (Hatch and Choate 1929). Secondly, the results were grouped into sand, silt and clay percentages and plotted onto a ternary diagram (Plumley and Davis 1956). Finally, the parameters of the percentage frequency distributions were calculated using the graphic techniques defined by Folk and Ward (1957) and McCammon (1962).

(ii) Roundness analysis

Roundness measurements on 100 grains from the 0.25 mm (1.25 to 2.0 ϕ ; medium sand-size) sieve size of 60 till samples taken from the Carsphairn Lane - Water of Deugh - River Ken area (samples taken from the Loch Doon basin were not analysed) were made in the laboratory using a binocular microscope. The procedures used were the same as those outlined above (p. 29), except that the Powers visual comparison chart was photo-reduced to the corresponding phi-size in order to facilitate accurate matching. To reduce operator bias in the analysis to an acceptable level, a colleague randomly presented the writer with samples that were unlabelled (Beal and Shepard 1956; Sneed and Folk 1958). The roundness counts were then undertaken, and only after completion of the exercise were the results matched with the true sample numbers. These were plotted on a ternary diagram and various statistical tests employed to analyse the data further.

(iii) Geotechnical properties

To determine whether any of the tills in the Carsphairn Lane - Water of Deugh area were susceptible to flow in the presence of water, tests to obtain their Atterberg limits were carried out in the Soil Mechanics Laboratory of Heriot Watt University.

The concept of the Atterberg limits applies to fine-grained soils or till in which the water content affects the physical properties, changing clay material from a solid to a liquid or slurry (Atterberg 1911). The plastic limit and the liquid limit of any soil/till refers to the boundary condition of the material between the plastic and semi-solid state and the liquid and plastic state

respectively. Thus the liquid and plastic limits of 20 till samples, from the cross-valley ridge, drumlin and valley-fill landforms in the Carsphairn Lane - Water of Deugh area, were analysed using the methods described by Akroyd (1964).

The methods used to determine the plastic limit of till samples may be summarised as follows.

- 1) A sample of approximately 15 gm weight was worked through a 0.5 mm (1 ϕ) sieve.
- 2) The sample was thoroughly mixed on a glass plate with sufficient distilled water to make it plastic enough to be shaped into a small ball.
- 3) The ball was rolled between the hand and the glass plate with enough pressure to form it into a thread.
- 4) When the diameter of the thread had decreased to 3.5 mm the specimen was kneaded together and rolled out again. This process was continued until the thread crumbled at 3.5 mm diameter.
- 5) This procedure was repeated for two more samples.
- 6) The crumbled threads were gathered into a bottle and their moisture content measured by weighing the container and contents and then drying them in an oven at a temperature of 110°C for 24 hours. After drying, the container and contents were again weighed. From these readings the moisture content was calculated using the equation:

$$m = \frac{W_w - W_d}{W_d - W_c} \times 100 \quad (1)$$

where: W_c = weight of container (gm),
 W_w = weight of container plus wet sample (gm),
 W_d = weight of container plus sample after drying out (gm),
 m = percentage moisture content.

The average of the three moisture contents was taken as the plastic limit of the till. This was recorded to the nearest whole number and expressed as a percentage.

The technique used for obtaining the liquid limit of the till samples may be summarised as follows.

- 1) A sample of 120 gm was worked through a 0.5 mm (1 ϕ) sieve and thoroughly mixed with distilled water until it acquired the consistency of a thick paste.
- 2) A brass cup and carriage (Casagrande 1932), mounted on a rubber block, was half-filled with the wet sample and the top levelled off.
- 3) The paste in the cup was divided along the cup diameter by means of a Casagrande Type grooving tool, leaving a V-shaped gap 2 mm wide at the bottom, 11 mm at the top and 8 mm deep.
- 4) The cup was lifted and dropped through 1 cm at a rate of two blows per second until the two parts of the sample touched for a length of 1.3 cm along the bottom of the groove. The number of blows at which this occurred was recorded and a small sample of material from the bottom of the groove was removed. If the number of blows exceeded 50 the result was not accepted and more water was added and the test started again.
- 5) The procedure given above was repeated four times using the same sample to which increments of distilled water were added at the beginning of each stage.

- 6) The moisture content of each small sample, corresponding to each of the number of blows, was calculated. The number of blows was plotted as ordinate on a log scale against its corresponding moisture content as abscissae on an arithmetic scale. A straight line was drawn through the plotted points. This line is called a flow curve and is defined by the equation

$$m = -F \log N + C \quad (2)$$

where: m = moisture content,

F = a constant - the flow index,

N = the number of blows,

C = a constant.

The moisture content corresponding to the 25-blow ordinate was read off as the liquid limit. This was recorded to one place of decimals and expressed as a percentage in the final results table.

The plastic limit test was carried out on all samples before proceeding with the liquid limit test. If the sample showed no capacity to develop a plastic limit then it was assumed that the till did not possess a liquid limit. Of the 20 till samples tested only three proved to have a plastic and liquid limit.

(iv) Lithological analysis

Many studies have successfully employed lithological analysis to assist in differentiating tills (Krumbein 1933; Jarnefors 1952; Dreimanis and Reavely 1953; Anderson 1955; Arneman and Wright 1959; Kaiser 1962; Gross and Moran 1971; May and Dreimanis 1976; Mills 1977a). Thus a lithological analysis of the two tills observed in the Carsphairn area was performed on two size ranges: viz. -4 to -8 ϕ

and 1.25 to 2.0 ϕ . The former was carried out in the field using many of the clasts employed in the till macro-fabric and roundness analyses. However, owing to the almost total dominance of greywacke rocks in this size range the results showed no differences between the two tills; these results will not be discussed further. A similar procedure was employed while the roundness characteristics of the 1.25 to 2.0 ϕ size particles were being determined. Interestingly, these results showed significant differences in the lithology and are therefore discussed in some detail in Chapter 8.

(v) Determination of carbonate content

As certain limestone formations of Ordovician age crop out to the north of the field area, it was felt that till differentiation might be aided further by assessing the amount of carbonate present in the samples. This assessment was made by using the Collins Calcimeter, an instrument that determines the percentage carbonate contained in a sample by measuring the amount of gas released by the reaction between the sample and 10 cc of concentrated HCl.

A pilot analysis of 22 till samples taken from various landforms in the Carsphairn Lane - Water of Deugh valley was initially undertaken. None of these samples showed any reaction with the HCl, indicating that the amount of carbonate present was negligible. The analyses were therefore discontinued.

CHAPTER FOUR

PREVIOUS STUDIES ON THE GLACIATION AND DEGLACIATION OF SCOTLAND

4.1 INTRODUCTION

This review of the literature is divided into two parts. First, the glaciation and deglaciation of Scotland as a whole is considered briefly in order to put the area examined in this study into perspective. Secondly, previous studies on the glacial features of the western Southern Uplands are reviewed.

4.2 THE LATE-DEVENSIAN IN SCOTLAND

The Late-Devensian ice-sheet is believed to have reached its maximal extent between 18,000 and 20,000 years ago (Boulton and Worsley 1965; Penny *et al.* 1969; Worsley 1970) when most of Scotland was ice-covered. The subsequent decay of this ice-sheet has been the subject of considerable debate, particularly with regard to major readvances.

Charlesworth (1926b) recognised a major readvance limit of Highland ice in southern Scotland, which he termed the "Lammermuir-Stranraer kame moraine". However, Sissons (1958a) and Kirby (1968, 1969) showed that much of the area supposedly covered by Highland ice was in fact occupied by Southern Uplands ice, while Sissons (1961b) demonstrated that Charlesworth's "moraine" was largely composed of fluvioglacial deposits. Synge (1956, 1963) described possible readvance limits in the Aberdeen area but Clapperton and Sugden

(1972, 1977) have shown that the pattern of meltwater channels and fluvioglacial deposits is inconsistent with the supposed readvance. Similar arguments hold for the rejection of Sissons' (1967a) "Aberdeen-Lammermuir Readvance" (Sissons 1974b, 1976).

The Perth Readvance was first recognised by Simpson (1933). His critical section in the valley of the River Almond, NW of Perth, comprised a basal till overlain by marine sediments (that he interpreted as varves) that were in turn covered by outwash. Subsequently, Sissons (1963, 1964) mapped the limit of the readvance in central and southern Scotland. McLellan (1969) also supported the concept of the readvance in central Lanarkshire, although he modified Sissons' limit.

De Geer (1935) correlated the "varves" described by Simpson with the Swedish varve chronology and suggested that they accumulated ca. 13,100 years ago. A mammoth tusk from stratified deposits beneath 10 m of till at Kilmaurs in Ayrshire yielded a date of $13,700 \pm 1300$, -1700 B.P. (Sissons 1967b), while deposits at Roberthill, near Lockerbie, Dumfriesshire (Bishop 1963) and Loch Droma in the NW Highlands (Kirk and Godwin 1963) implied that these areas were free of ice by 12,900 B.P. and 12,800 B.P. respectively. It was therefore suggested that the Perth Readvance culminated between 13,500 and 13,000 B.P. (Sissons 1967a, b).

However, more recent evidence casts doubt on the readvance. A date of >40,000 B.P. (Shotton et al. 1970) for a reindeer antler from, apparently, the same stratigraphical position as the mammoth tusk at Kilmaurs makes the dating of the overlying till at this site equivocal. Similarly a date of >36,900 B.P. (Shotton and Williams 1973) for marine shells from fluvioglacial deposits within the supposed limit of the Perth Readvance at Stranraer does not accord

with the proposed readvance. Dating of a woolly rhinoceros bone from fluvioglacial gravels beneath till at Bishopbriggs near Glasgow to $27,500 \pm 1370$, -1680 B.P. (Rolfe 1966) further suggests that at least some of the readvance evidence relates to the build up of the Late-Devensian ice-sheet rather than to its deglaciation. Francis *et al.* (1970) could find no morphological evidence for the Perth Readvance in the Stirling area, while Paterson (1974) re-investigating the critical area in the Almond valley originally studied by Simpson, suggested that the deposits were inconsistent with a major readvance. He argued that the rhythmically-bedded deposits represent frequent discharges of sediment down a prograding delta front and are not varves. Evidence for the Perth Readvance is therefore unsatisfactory and the postulated event must be treated with considerable scepticism (Sissons 1974b, 1976; Price 1975).

There is a recent exception to the sequence of papers dismissing the evidence for readvances. Robinson and Ballantyne (1979) have interpreted end moraines and striae in the NW Highlands (Wester Ross) as marking the limit of a readvance that took place

between the Late-Devensian ice-sheet maximum and the Lateglacial Interstadial*. However, no stratigraphical evidence was presented to support the readvance hypothesis and it is possible that the features described represent minor fluctuations of the ice-sheet margin during deglaciation (cf. Bowen 1978).

Evidence for the final phase of glacier activity in Scotland is much less tenuous. Indeed, it was recognised over a century ago by the Geikie brothers. Simpson (1933) correlated the prominent end moraines at Menteith in the Forth Valley with those by Loch Lomond and the term Loch Lomond Advance (or Readvance) is now used to describe the

* The terminology and chronology of events referred to in this thesis are as follows:

- | | |
|--------------------------|--|
| Lateglacial | : the terminal phase of the Late-Devensian period, spanning the time interval from ca. 14,000 B.P. to 10,000 B.P. (Shotton 1973). This period includes Jessen-Godwin pollen zones I, II and III. |
| Lateglacial Interstadial | : the period between the climatic amelioration that occurred between ca. 14,000 B.P. and 13,000 B.P. and the beginning of the climatic deterioration that took place ca. 11,000 B.P. (Gray and Lowe 1977). |
| Loch Lomond Stadial | : the period between the start of the climatic deterioration at ca. 11,000 B.P. and the beginning of the Flandrian (ca. 10,000 B.P.)(Gray and Lowe 1977). |
| Postglacial | : the period from Jessen-Godwin pollen zone IV, which is virtually contemporaneous with the beginning of the Flandrian (Shotton 1973), to the present day. |
| postglacial | : the period since final deglaciation at any point. |

event. Eight radiocarbon dates from five sites where marine shells are associated with the former glaciers all lie between 11,800 and 11,300 B.P., implying that the glaciers reached their maximal extent later (Sissons 1967b; Peacock 1971; Gray and Brooks 1972). As the only subsequent period climatically severe enough to permit glaciers to develop occurred during the Loch Lomond Stadial, the readvance is assigned to this cold period (Sissons 1974b, 1976).

Although the stadial is thought to have spanned the time period ca. 11,000 - 10,000 B.P. (see footnote p.43), radiocarbon dates of $10,290 \pm 180$ and $10,520 \pm 330$ B.P. from the NW part of Rannoch Moor (Lowe and Walker 1976; Walker and Lowe 1977) seem to imply that this major centre of ice accumulation was ice-free before ca. 10,200 B.P. However, it is possible that "old" carbon in the granitic rocks of the area may have contaminated the dated material (Sutherland, in press).

The distribution of pollen sites with a Lateglacial stratigraphy has helped to determine the extent of the advance, for such sites show that the glaciers did not reach them (Sissons 1976). In addition, morphological mapping of hummocky, lateral and terminal moraines and boulder spreads together with the contrast in size of periglacial features across the presumed ice limits have been used to delimit the advance in Scotland (e.g. Sissons 1974a, 1977; Ballantyne and Wain-Hobson 1979).

Peacock (1970) argued that the large volume of ice that existed in western Inverness-shire during the Loch Lomond Stadial could not have accumulated in the short time available and suggested that ice was present in this area throughout the Lateglacial. Similarly, Sugden (1970) from his morphological mapping in the western Cairngorms

and Spey valley suggested that a large ice mass survived there through the Lateglacial Interstadial. Sissons (1974b, 1976) and Sissons and Walker (1974), however, maintained that glaciers disappeared completely from Scotland by 12,500 B.P. and built up anew during the Loch Lomond Stadial. Evidence for the latter contention includes at least 58 Lateglacial pollen sites (Sissons 1976, Figure 6.2), which demonstrate that large areas were free of ice during the Lateglacial Interstadial. Radiocarbon dates from basal organic deposits at several of these sites suggest deglaciation of these areas by ca. 13,000 B.P. (e.g. Kirk and Godwin 1963; Pennington 1975; Lowe 1978). In accord are a mean July temperature in SW Scotland 13,000 years ago of ca. 15°C inferred from coleoptera (Bishop and Coope 1977) and the apparent retreat of polar waters from the western shores of the British Isles ca. 13,500 B.P. (Ruddiman and McIntyre 1973; Ruddiman *et al.* 1977).

4.3 THE LATE-DEVENSIAN IN THE WEST-CENTRAL SOUTHERN UPLANDS

In 1863, A. Geikie described striae and moutonnée forms that convinced him that ice moved NE from the western Southern Uplands towards the Central Lowlands of Scotland. In 1865 he further suggested that the Southern Uplands formed a centre of dispersion for the southern part of the Scottish ice-sheet, illustrating the efficacy of this ice by drawing attention to the impressive rock basin occupied by Loch Doon and the scattering of Loch Doon granite boulders far to the north of the outcrop. A. Geikie also tentatively suggested that a second and later series of glaciers existed, which were confined to the major valleys.

In 1868 Jolly also postulated the existence of a later "partial glacier period". In addition, he mapped a series of "moraines" in the Merrick - Rhinns of Kells area that he interpreted as marking the successive retreat stages of this later valley glaciation. Only the eastern edge of the study area is covered by a Geological Survey memoir (Skae et al. 1877) and this only briefly. Using striae and the distribution of granite erratics Skae et al. inferred an essentially radial flow of ice from the Merrick - Rhinns of Kells uplands and suggested that the high ground around Cairnsmore of Carsphairn nourished an additional source of ice that deposited erratics on the Culmark, Fingland and Stroanpatrick Hills to the east and SE. Moreover, they reaffirmed the evidence for a later, independent valley glaciation by drawing attention to a series of "moraines" located in the Water of Deugh and River Ken valleys (the cross-valley ridges referred to in Chapter 1). These "moraines" were described as being "arranged in concentric lines, sometimes conical in shape, but generally assuming the form of narrow ridges which often trend towards the centre of the valley" (Skae et al. 1877, p.41). Later Forsyth (1892) briefly mentioned similar features NW of Carsphairn, which he interpreted as being formed by meltwater erosion of till.

A. Geikie's (1887) map of ice movements in Scotland indicated several minor centres of radiation in the Southern Uplands, but he regarded this area as having been covered by one vast ice-sheet that "moved outwards and downwards into the low ground on all sides" (1887, p.312). J. Geikie (1894) believed, like his brother, that the ice-sheet was resolved into valley glaciers as the high ground

emerged during deglaciation. The absence of large moraines led J. Geikie to suggest that there were few, if any, long pauses in the retreat of the valley glaciers. The presence of well-developed morainic mounds in some of the valley heads, lying on top of the basal till, indicated to him that there had been a readvance of ice after the general retreat of the ice-sheet. He went on to suggest that the interval between the dissolution of the ice-sheet and the valley glaciers was one of milder climate. On the fringe of the Scottish Highlands the valley glaciers had ploughed up the deposits of the "100 foot sea" and therefore J. Geikie argued that the valley glaciers of the Southern Uplands and Highlands represented a return to glacial conditions, on a limited scale, after the "interglacial" period.

Smith (1898) described the widespread distribution of granite boulders in Ayrshire, and suggested that they had been transported north and NW by ice flowing from the Loch Doon basin.

Charlesworth (1926a) produced a useful synthesis of work on the western Southern Uplands. He stated that during the early phase of glaciation all the higher hills of that area nourished independent glaciers. At the maximum the centres of ice dispersal lay over the highest ground, coinciding with the present-day Merrick - Corserine watershed and extending eastwards into the Cairnsmore of Carsphairn upland and Lowther Hills. From this NE-SW-trending ice-shed ice radiated down the major valleys (i.e. Glen Trool and the valleys of the Dee, Doon, Deugh and Ken). From the distribution of Loch Doon granite erratics Charlesworth inferred that ice crossed the Merrick range and spread out over the headwater valleys of the Cree.

Charlesworth interpreted the retreat of the ice-sheet from the occurrence of "moraines" and outwash fans in various valleys in the western Southern Uplands. However, as more recent work has shown (Stone 1957, 1959; Sissons 1961a; Cullingford 1962), many of the "moraines" are composed of sand and gravel and are therefore of fluvioglacial rather than glacial origin.

Gregory (1926) described "moraines" in SW Scotland and concluded that they were limited to valleys associated only with those mountain groups that had considerable areas over 460 m O.D. In particular he commented on "moraines" located between Dalmellington, Carsphairn and St John's Town of Dalry.

The relationship between Highland ice and Southern Uplands ice along the southern edge of the Central Lowlands of Scotland has long been a controversial topic. A. Geikie (1863), Gregory (1915) and Charlesworth (1926a) all suggested that Southern Uplands ice moved north into the Central Lowlands. However, Charlesworth (1926a) stated that the Thankerton "kame" in the Clyde valley was deposited at the margin of Highland ice, an interpretation accepted by Linton (1933). Sissons (1961a) and McLellan (1969) have subsequently demonstrated that the "kame" was formed in association with Southern Uplands ice.

Richey et al. (1930) contended that farther west the contact of Highland and Southern Uplands ice lay along the line Ballantrae - Girvan - Maybole - New Cumnock, suggesting that this line marked the southern limit of Highland erratics (including Glen Fyne granite) and of till containing marine arctic shells swept from the bed of the Firth of Clyde. This point is important as it implies that, at the time Highland ice pushed into Ayrshire from the Firth of Clyde to

deposit the shelly drift, a considerable mass of ice existed in the Southern Uplands. The main centre of the latter ice mass lay over the Loch Doon basin and granite erratics from here have been distributed as far north as the shelly drift limit.

The interpretation of "morainic mounds" in some Southern Uplands valleys (Young 1864; J. Geikie 1894) as representing a readvance of ice has been supported by Price (1963) and Sissons (pers. comm. 1975), who recorded hummocky moraine of presumed Loch Lomond Stadial age from the Tweedsmuir Hills, as did Clapperton (1970) from the Cheviots. No detailed map of these landforms has yet been produced from the Loch Doon basin, however.

4.4 SUMMARY AND CONCLUSIONS

It is thus clear that the limited literature of recent years has only amplified, by the presentation of details, the generalisations made before the close of the nineteenth century. The Southern Uplands are known to have nourished an ice-sheet that moved out radially from the centres of high ground. The movement northwards was deflected to the east and west by the presence of Highland ice. The last ice-sheet to occupy the area considered in this thesis originated in the Southern Uplands. It is the features resulting from the wastage of this ice-sheet that will be analysed in detail. A local glaciation confined to the higher hills took place after the decay of the Late-Devensian ice-sheet and produced distinctive moraines. These landforms are believed to be related to the Loch Lomond Stadial and their distribution is considered in the latter part of this thesis.

CHAPTER FIVE
LANDFORMS OF GLACIAL EROSION
AND FORMER DIRECTION OF ICE MOVEMENT
IN THE STUDY AREA

5.1 INTRODUCTION

It has long been recognised that, although the principal elements of the relief of Scotland were fashioned during the Tertiary period, glaciation frequently resulted in extensive modification of these features. Evidence for this modification is well displayed in the western Southern Uplands, especially in the Loch Doon basin and on the Merrick and Rhinns of Kells ranges. Here, glacially deepened troughs, breaches, cols and areas of ice-scoured bedrock are dominant features of the landscape, landforms of glacial deposition being very much of secondary importance. Major erosional features such as occur in the western Highlands are lacking, however, for the belt of high ground bordering the Loch Doon granite area is narrow and the breaches that do exist are short and of only modest dimensions.

This landscape in which erosional landforms predominate stands in direct contrast to the smooth, rounded slopes of the Lamermuir and Moorfoot Hills in the eastern Southern Uplands (Haynes 1977). This general difference is also, in part, a reflection of the difference in rock type, as it is on the igneous and metamorphic rocks of the west that the effects of glacial erosion are most evident.

In this chapter, the landforms of glacial erosion are described and use is made of their varied orientations and alignments in order

to provide a basic pattern of the direction of ice movement. These observations are then combined with the distribution of glacial erratic boulders from five different bedrock sources, with glacial striae and with ice-moulded landforms to produce a more detailed picture of the ice movements and thicknesses that probably existed during the stage of maximum ice-sheet development in the study area.

5.2 GLACIAL TROUGHS

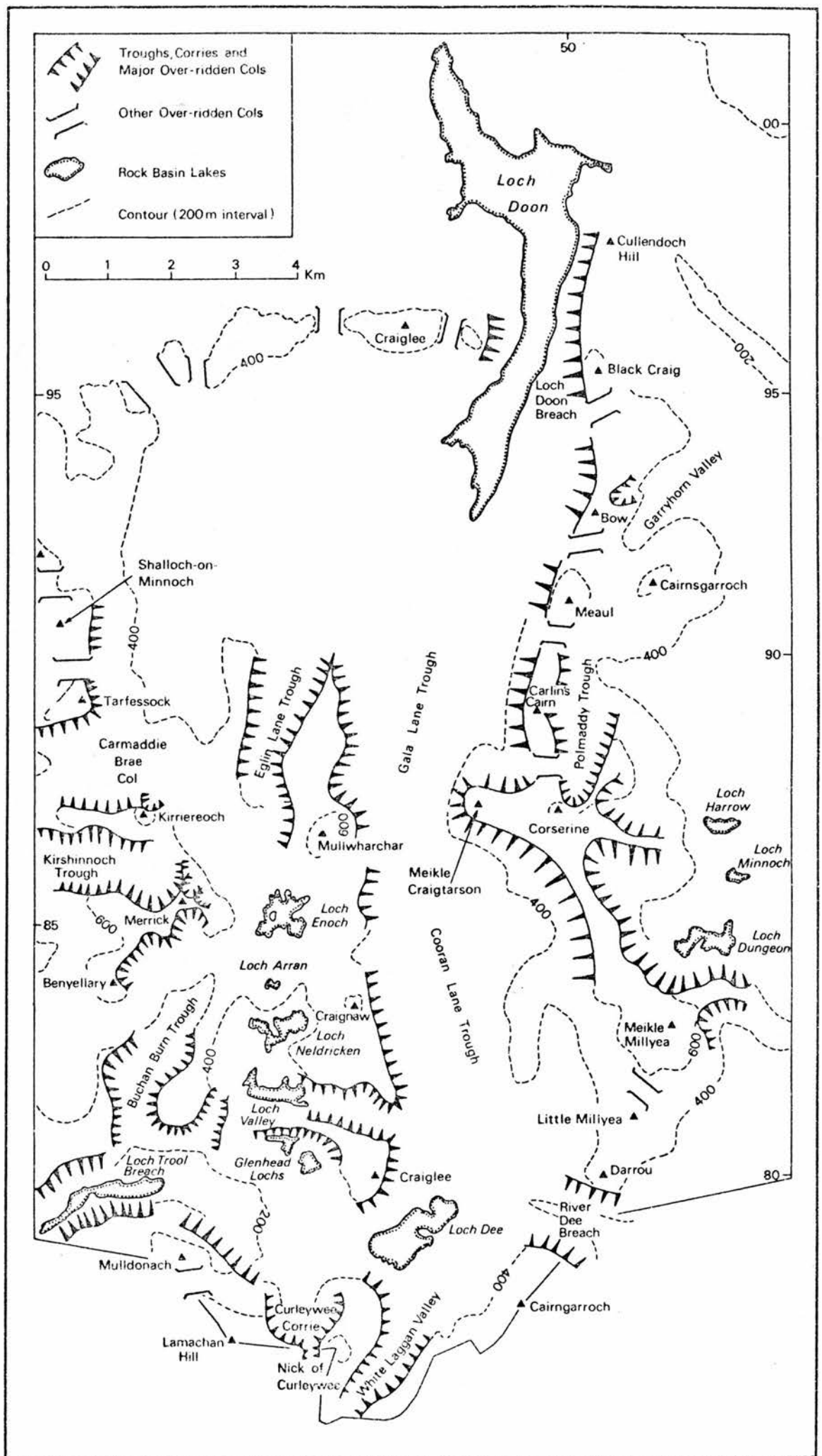
Adequate evidence exists to show that glacial erosion was most severe in Scotland in and immediately around the main centres of ice accumulation (Linton 1963; Sissons 1967a). The most important of these areas during the Late-Devensian glaciation lay in the western Highlands (Sissons 1976, Figure 5.1), the major ice dome extending from Loch Lomond to Loch Broom. In numbers, depth and variety of form, the glacial troughs radiating from this composite dome provide the most striking examples of glacial erosion in Scotland. However, in the Southern Uplands context the Loch Doon basin furnishes, although much less impressively, similar proofs of the efficacy of erosion by ice.

The most impressive of these troughs extends for ca. 16 km N-S between Loch Doon and Loch Dee (Figure 5.1). It is bounded by the adamellite hills of Hoodens Hill, Mullwharchar and Craignaw to the west and by the Rhinns of Kells to the east. The trough is confluent with the Loch Doon glacial breach in the north, while to the south it merges with the Water of Dee breach and the ice over-ridden col at the head of White Laggan Burn. This U-shaped trough appears to be a composite feature, being constricted in its central section by the



Figure 5.1

**Major glacial troughs, breaches, over-ridden
cols and rock basin lakes of the Loch Doon
basin and surrounding uplands.**



summits of Mullwharchar and Meikle Craigtarson. Both to the north and south of this constriction, the trough widens to almost 3 km in places and is bounded, especially on the western side, by the steep, ice-scoured granite cliffs of Snibe Hill, Craignaw and Yellow Tamach. At one point, by Dungeon Hill, the trough wall rises almost vertically for fully 150 m above the peat-covered floor. It has been suggested that the ground between Mullwharchar and Meikle Craigtarson formed a pre-glacial watershed (Peach and Horne 1910), as this col-like area is higher in altitude than that to the north and south. Although this section of the valley forms the present-day watershed, and evidence collected from granite erratics and striae suggests that it was also the location of an ice-shed, it is difficult to demonstrate that any substantial breaching by ice has taken place at this point.

A glaciated through-valley extends E-W from Loch Dee to Buchan Farm (Figure 5.1) in the southern part of the granite basin (continued in a westerly direction as the Glen Trool breach). This feature has a somewhat subdued morphology since it has been modified by overriding ice. This effect can be largely explained by the orientation of the through-valley at right-angles to the main direction of ice movement in this area. Thus it is suggested that the trough was only effectively utilised during the early stages of ice build-up, when valley glaciers were able to feed into it from Curleywes corrie, the Glenhead corries and the valleys of the Gairland and Buchan burns. The latter two now remain as valleys hanging markedly above the main trough, the discordance in level between the two tributary valleys and the main valley amounting to 150 m.

Moreover, the funnelling of large volumes of ice into the upper reaches of, what is now, Glen Trool would have the effect of rapidly

establishing an escape route across the upland mass of metamorphic rocks to the SW, leading eventually to its breaching.

From the mapped limits of Loch Lomond Advance glaciers it may be inferred that during the early stages of ice-sheet build-up in the Loch Doon basin, valley glaciers were nourished under the eastern slopes of the Merrick range. This inference is supported by a series of U-shaped troughs that extend in a north and north-easterly direction towards Loch Doon (Figure 5.1). Although small in magnitude, the longest being 6 km (occupied by Eglin Lane), the troughs suggest the early, and perhaps the later, directions of ice movement in this part of the basin.

To the west of the Merrick range glacial troughs such as the valleys of Kirshinnoch and Cross Burns have been cut into the upland area of metamorphic rocks, extensively modifying their pre-glacial form (Figure 5.1). The troughs are less than 3 km in length, for the upland surrounding the granite basin at this point is narrow. Steep ice-scoured cliffs up to 270 m high, which include precipitous rock faces, on the Black Gairry (north face of the Merrick) and the north and south faces of Kirriemoch Hill, testify to the intensity of glacial excavation in these E-W orientated troughs. The valley headwalls are, however, not so impressive as they have been modified and reduced in height by over-riding ice originating from the Loch Doon basin, which from other evidence (see Section 5.6) is known to have had a strong westerly flow. These troughs may be classified as Alpine type (Linton 1963), as they are characterised by ice accumulation in valley heads overlooked by higher ground with discharge into what were probably pre-glacial valleys.

Although the western slopes of the Rhinns of Kells formed one wall of the Gala-Cooran Lane trough, troughs are virtually non-existent on the eastern side of the range. The upper reaches of the Garryhorn and Polmaddy Burns provide the only good examples of troughs (Figure 5.1). The latter valley is small in size (3.5 km long and averaging 0.75 km in width) and modified by large amounts of till and peat on its floor. In places the trough walls, particularly below the summit of Carlin's Cairn, are steep and precipitous, often exceeding 120 m in height. The orientation and development of this trough were to some degree controlled by local geological factors, the northern 3 km being excavated along the strike of a series of intensely folded shales, mudstones and radiolarian cherts. This compares with the Glen Trool breach, which displays a similar relationship on the same rock types (see Section 5.3). Elsewhere in this area the valleys are broad and open, some terminating in well developed corries at their western extremities.

5.3 GLACIAL BREACHES

One aspect of glacial erosion that is well represented in the study area is the breaching of pre-glacial watersheds to produce new through valleys where perhaps only cols existed previously. These features have been well documented in the western Highlands of Scotland by Linton (1951, 1959, 1963), Dury (1953) and Sissons (1967a, 1976), but have received only scant attention in the western Southern Uplands (Peach and Horne 1910; Sissons 1976). In this latter area evidence provided by the literature suggests that for long periods ice moved outwards from the Loch Doon basin. The related pattern of radiating

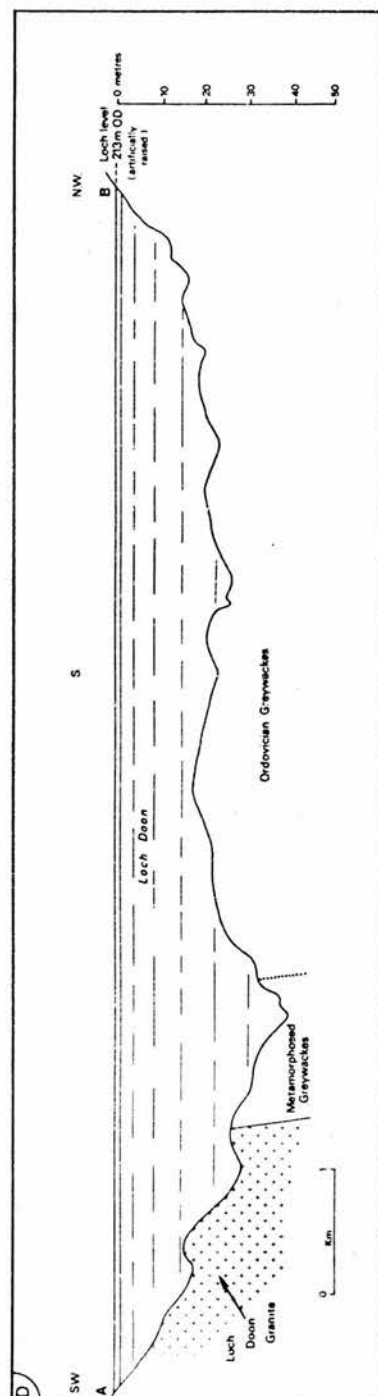
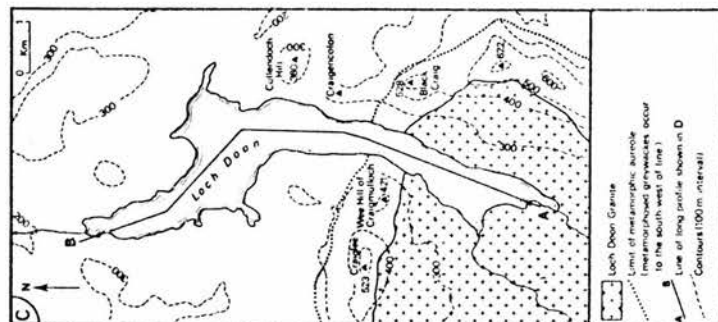
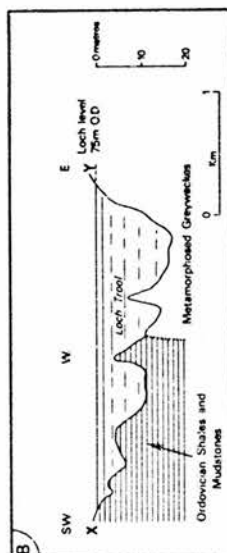
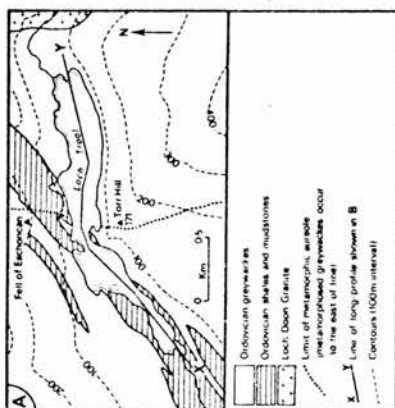
breaches and over-ridden cols is brought out in Figure 5.1. Among the important elements of this valley system are Glen Trool, the valley of the Black Water of Dee and the Loch Doon valley. Once well established, these deeper breaches were able to function at times of less extensive ice cover and operated as narrow connecting valleys between the broad glaciers that occupied the major valleys on either side. A description of these features is therefore necessary in order to provide supplementary evidence on the direction of ice movement as well as giving an indication of where the major ice streams were operating and eroding during the period of maximum ice-sheet development.

Loch Trool is located in a glacial breach that cuts clean through the metamorphic rocks surrounding the Loch Doon granite intrusion. Although the breach is approximately 4 km long, for 2 km between the SW end of the loch and Stroan Farm only its northern wall is well developed (Figure 5.2A, B). The upland area to the south at this point is much lower and displays evidence of over-riding by ice. The gap is not only confined to the area within the metamorphic aureole, but extends for over 3 km outside the margin as mapped on the 1:63,360 Geological Survey map (Sheet 8). Within the aureole the floor of the breach, at loch surface level, reaches 600 m at its widest point. One kilometre farther west, however, just outside the aureole, it narrows rapidly to little more than 250 m, and it is here that the breach is most impressively developed. The reasons for this are not clear, as the writer could find no evidence for relief or structural control in this section of the breach. However, at this point, below the summit of the Fell of Eschoncan (347 m) on the northern side of the gap, steep, ice-scoured cliffs

Figure 5.2

Location, geology and morphology of the Loch Trool and Loch Doon glacial breaches:

- A. Geology and relief of Glen Trool;**
- B. Long-profile of Loch Trool (soundings after Murray and Pullar 1910);**
- C. Geology and relief of the Loch Doon breach;**
- D. Long-profile of Loch Doon (soundings after Murray and Pullar 1910).**



descend 220 m to the shores of Loch Trool, which is at least 15 m deep at this point (Murray and Pullar 1910). This suggests that 235 m of rock has been excavated by ice during the formation of the trough.

The influence of local bedrock geology on the selectivity of ice erosion is demonstrated by the configuration and alignment of the Loch Trool breach (Figure 5.2A). Between the granite/metamorphosed greywacke contact zone and Torr Hill the gap is largely excavated in metamorphosed greywackes and trends E-W. West of Torr Hill, however, this orientation changes to NE-SW and is maintained until the breach becomes an indistinct feature by Stroan Farm. This change in alignment corresponds to a series of thin bands of black shale, red mudstones and radiolarian cherts folded into tight, complex isoclines that traverse the valley at this point (Gardiner and Reynolds 1932). These strata strike to the SW and their structural weakness is confirmed by a series of porphyritic dykes that crop out in the vicinity and have the same strike. This suggests that these strata were more susceptible to ice erosion than the metamorphosed greywackes, and therefore influenced the direction of ice movement. The depth of Loch Trool increases down valley from where the weaker strata cross the floor of the breach, reaching 11 m at one point (Figure 5.2B). The degree of downcutting, however, is less than that to the east (i.e. in the metamorphosed greywackes), as the confining nature of the relief, with its concomitant funnelling effect on ice movement, exercised less of a control in the former area.

The second major breach occurs at the SE edge of the granite basin and is at present occupied by the Black Water of Dee (Figure 5.1).

It is much less impressive than the Glen Trool breach as the belt of upland on this margin is much narrower, being little more than 2 km wide. The ground on either side of the gap exceeds 450 m O.D. in the summits of Darrou and Cairngarroch, while the floor lies at ca. 210 m O.D. It is orientated WNW-ESE and is confluent with the Cooran Lane trough to the NW, which suggests that it provided one of the routeways for the evacuation of ice from the Loch Doon basin.

The remaining breach of any significant size forms a northerly continuation of the Gala Lane trough and is occupied by the rock basin lake of Loch Doon (Figure 5.1). The breach is very constricted where it is cut in the metamorphic rocks and averages 800 m in width at the level of the loch surface. On the 1:63,360 Geological Survey map the metamorphic aureole, at this point, is drawn as extending for ca. 1 km north of the granite contact and it is within this belt of rocks that the breach is most striking (Figure 5.2C). The ground on either side rises to 421 m in the Wee Hill of Craigmulloch to the west and 528 m in Black Craig to the east. The eastern wall of the breach extends for 2.5 km north of the outer margin on the metamorphic aureole and includes the western slopes of Craigencolon and Cullendoch Hill. However, the western wall becomes much lower in altitude and less well defined north of the metamorphic outcrop. The walls of the breach are steep and in places precipitous, while the lower slopes, although mantled with till in places, display well-developed moutonnée forms with striated surfaces indicating erosion by a powerful ice-stream flowing north from the Loch Doon basin.

A series of cols that show signs of having been over-ridden by ice also occurs on the metamorphosed greywacke rocks (Figure 5.1).

Between Glen Trool and the Black Water of Dee there are three through-cols that, on the basis of evidence from glacial erratics (Section 5.6) are known to have carried glaciers. Between Mulldonach and Lamachan Hill the Nick of the Lochans col is 40 m deep with its floor at an altitude of 504 m and orientated NE-SW. The Nick of Curleywee, which breaches the back wall of Curleywee corrie, is 30 m deep and is another through-col; its floor is at an altitude of 558 m. Finally, at the head of the White Laggan valley, which itself has been glacially overdeepened, a through-col 50 m deep and trending NNE-SSW at an altitude of 410 m is well marked. Evidence presented by Charlesworth (1926a) and fieldwork carried out by the present writer, show that there is little doubt that these through-valleys were cut by ice flowing in a southerly direction. Moreover, the relatively high altitude of their floors compared with that of the granite basin implies that they were over-ridden at a later stage in the glaciation, when a considerable ice mass had built up to the north. This interpretation is supported by the location of the Nick of Curleywee col, for this is cut in the backwall of a north-facing corrie.

Further examples occur in the Merrick range and in the upland area immediately north of the granite outcrop (Figure 5.1). In the former, all the cols between the major summits display signs of having been over-ridden by ice. The estimated values for the amount of downcutting within the cols in the Merrick hills, as shown in Table 5.1, decrease progressively away from Merrick summit. Moreover, there is a corresponding reduction in the impressiveness of these features in the same direction. For example, the col between Shalloch-on-Minnoch and the unnamed summit to the north is ill-defined

Table 5.1: Altitudes and depths of glacially modified cols in the Merrick hills.

Cols between major summits		Col floor altitude: metres	Altitude of top of wall: metres	Depth: metres
north ↓	Benyellary - Merrick	661	701	40
	Merrick - Kirriereoch	634	762	128
	Kirriereoch - Tarfessock	592	676	84
	Tarfessock - Shalloch-on-Minnoch	619	686	67
	Shalloch-on-Minnoch - unnamed summit (659 m)	622	655	33

and displays only limited evidence of having been modified by ice. In contrast, the Carmaddie Brae col, lying between Kirriereoch and Tarfessock, is exceptionally well developed. This col comprises a smoothly undulating surface 1.4 km wide that descends steeply to lowland areas on both its eastern and western flanks, the latter forming the floor of the trough developed in the valley of Cross Burn (Figure 5.1). On both the northern and southern sides of the col, steep rocky cliffs rise from the floor to 670 m O.D., implying that the col has been reduced in altitude by some 80 m.

These differences in the degree of modification can be largely explained by the influence of relief on ice movement. Charlesworth (1926a) suggested, and this has been subsequently confirmed in field evidence collected by the writer, that the area by Merrick summit lay toward the western extremity of an ice-shed that lay across the centre of the Loch Doon basin, and that from this area ice flowed in

a westerly direction into the Cree lowlands. Away from this zone, however, flow was generally to the north or to the south, controlled by the relief, thus providing little scope for lateral movement across the northern parts of the Merrick range.

In the area to the north of the granite outcrop four small cols show similar effects of utilisation by ice streams. The col floor altitudes range between 305 m and 380 m O.D. They are much less impressive than the over-ridden cols of the Merrick range, for the hills in which they occur have themselves been greatly reduced by glacial erosion.

The distribution of granite erratics indicates that at certain points ice from the Loch Doon basin spilled over the Rhinns of Kells range and into the Carsphairn Lane - Water of Deugh - River Ken valley. The overdeepened cols between Meikle Millyea and Little Millyea summits in the south and between Bow and Meaul in the north of the range furnish confirmatory evidence for such movement (Figure 5.1). The former is 30 m deep, with its floor at 550 m O.D. and the latter 50 m deep at 560 m O.D. There are certain cols in the same hills, however, that display a greater degree of overdeepening than those mentioned above, but that lack evidence, in the form of granite erratics, to confirm that they were utilised by ice. The "Riders Gap" between Carlin's Cairn and Corserine summits, 90 m deep with its floor at an altitude of 706 m, provides one example. A second occurs between Meaul and Carlin's Cairn and is 80 m deep; its floor lies at an altitude of 620 m.

It is interesting to note that these two cols are the most impressive within the whole of the Kells range and are located close to the ice-shed that, according to Charlesworth (1926a), lay across the

Corserine area. This shows a similar pattern to the through-cols developed in the Merrick range farther west. As the evidence for ice movement in this part of the Rhinns of Kells is less clear than in the Merrick range, it will be discussed below with reference to the distribution of Loch Doon granite erratics.

A basic reason for the development of this series of breaches and over-ridden cols is that for considerable periods, the highest part of the ice-sheet was situated in the central granite basin, with the result that ice seeking to escape had to force its way through the surrounding barrier of hills. At such times it is probable that the whole area shown in Figure 5.1 was beneath an ice-sheet. This view is supported by evidence provided by the distribution of glacial erratics (Section 5.6). Thus at this time, the most rapid erosion would still take place along the valleys for here the ice would be thickest and basal ice velocities greatest (cf. Holmes 1937; 1952; Goldthwait 1973). Uncertainties must remain concerning the glacial origin of all of the breaches, for if the Loch Doon granite mass took the form of a basin prior to glaciation, then outlet valleys through the surrounding hills of metamorphosed greywacke rocks probably existed in order to drain it. Despite this possibility, there is little doubt that there was a strong tendency towards the development of a system of valleys radiating from the area of maximum ice accumulation. Where suitably aligned valleys already existed the ice utilised them and deepened them. Where they did not exist the ice cut new ones, breaching pre-existing watersheds as it did so. A further complication exists, however, in that the pattern of glacial troughs seen at present is the end product of a long and complex series of ice

movements. Directions of movement must have varied greatly at different times. Yet, the radial pattern displayed by the Glen Trool, Water of Dee and Loch Doon breaches testifies to the importance of this basin as a centre of ice accumulation. This radial movement could only occur, however, at times when ice nourished on the adjacent hills had accumulated to a sufficient thickness in the basin. Thus at times of only limited ice cover the movement of ice was essentially into the basin, not out of it. That such conditions prevailed during the closing stages of the last glaciation (i.e. during Loch Lomond Advance times) is shown by the moraines on the floor of the basin that were deposited by glaciers nourished on the surrounding hills (see Chapter 13).

5.4 ROCK BASINS

Additional evidence of the intensity of glacial erosion in the western Southern Uplands is provided by the presence of numerous rock basins, the dimensions of these basins being to a large extent revealed by the lakes that fill them. There is a contrast between the eastern Southern Uplands, where lakes occupying rock basins are absent, and the Loch Doon basin, where they are common (Peach and Horne 1910).

The effect of ground configuration on the excavation of rock basins is seen in the occurrence of the principal lakes of the Loch Doon basin in the major glacial breaches (Figure 5.1). Their presence in these locations provides convincing evidence that these breaches were gouged out by the ice as it was forced more rapidly through the relatively narrow gaps.

Figure 5.2C, D illustrates the effects of constriction, in the Loch Doon rock basin, on the capacity of ice to erode even the toughest bedrock. The cross-section (Figure 5.2C) is based on data from the bathymetrical survey carried out by Murray and Pullar (1910), although it should be noted that in most instances the depth figures tend to be minimal because of deposition in the lake during and since deglaciation. Moreover, since 1930, the maximal water level in Loch Doon has been raised artificially by approximately 8 m: thus the depths have been adjusted accordingly. The deepest sounding (39 m) occurs where the valley is constricted by the Wee Hill of Craigmulloch and Black Craig, both of which are composed of metamorphosed grey-wackes. Below this point the lake widens and its floor forms a shallower basin where it emerges from the higher hills onto the lower ground. Although the bedrock here is relatively weaker, the depth of the lake averages only 10 m. This suggests that after the ice had passed through the valley constriction, where vertical incision was intensified, its capacity to erode was much reduced and this is reflected in the shallower nature of the northern part of the basin. Similarly, in Loch Trool (Figure 5.2B) the deepest sounding (16 m) occurs where the valley is very constricted. The basin gradually shallows towards the SW even though it is excavated in a series of weaker shales and mudstones.

The effects of local bedrock geology on the development of rock basins is further evidenced by the location of Loch Dee, which lies at the confluence of two glacial troughs (Figure 5.1). The rock basin containing Loch Dee is excavated in the structurally weaker hypersthene rocks that crop out at the SE corner of the Loch Doon intrusion (Ruddock 1969). The efficacy of ice erosion on these rocks is

illustrated by the adjacent upland mass of Craiglee (531 m), which is carved in harder adamellite rocks. The SE face of this upland area descends over 300 m by a series of steep, and in places precipitous, ice-scoured cliffs to the floor of the basin (lying at only 214 m O.D.). Moreover, it is significant that the majority of the larger rock basin lakes occur within the outcrop of the Loch Doon granite and on the granodiorite in particular. The Lochs of Glenhead, Lochs Valley, Neldricken, Arran and Enoch are all located where ice-scoured bedrock is ubiquitous. Each, except Loch Valley (which is partly drift-dammed), is held up by a rock bar or step. Unfortunately, the depths of these lakes have not been sounded because of their inaccessibility. Loch Enoch, which at an altitude of 520 m is the highest upland lake in the Southern Uplands, is quoted by Jardine (1966) as having a maximum depth of 39 m, although he gives no reference source for this figure.

Outside the granite outcrop, rock basin lakes are confined to the metamorphosed Ordovician sediments. These are located in the corries on the eastern flanks of the Rhinns of Kells and include Lochs Dungeon, Minnoch and Harrow (Figure 5.1). The largest is the Loch Dungeon basin, which is partly dammed by a moraine. However, its deeper western basin is a true rock basin; the deepest sounding here being 29 m (Murray and Pullar 1910).

5.5 CORRIES

The corrie (cirque) has long been recognised as one of the most characteristic landforms of glacial erosion, and for the purposes of this study is defined as " . . . a hollow, open downstream but

bounded upstream by the crest of a steep slope ('headwall') which is arcuate in plan around a more gently sloping floor" (Evans and Cox 1974). Using this definition the writer has mapped eleven corries in the field area. This compares with Linton (1959) who identified nine. An attempt was made to use these features as supplementary evidence in order to identify the areas of initial ice build-up and movement within the area. This exercise proved impracticable because the corries are few in number and also different conditions must have prevailed when the ice-sheet was at its maximum.

Charlesworth (1926a) has shown that in places on the Merrick and Kells ranges there is unequivocal evidence to demonstrate that the surface of the last ice-sheet stood at least 840 m above present sea level. This implies that the majority of the corries in the field area were submerged beneath the ice-sheet and this probably on numerous occasions. In some cases, this invading ice has reduced the gradient of the headwall, as in the case of the trough heads developed in the Cross and Kirshinnoch valleys, or has breached the corrie headwall, as in Curleywee corrie.

However, certain inferences may be made from the location of the corries. Six of the corries defined within the field area overlook the Loch Doon basin and of these, five contain evidence of having been occupied by glaciers during the Loch Lomond Advance. This implies that before the ice-sheet attained its maximum, glaciers flowed into the basin from the corries in the surrounding hills. Further, three corries, two of which contain evidence for the former presence of Loch Lomond Advance glaciers, occur on the eastern flanks of the Rhinns of Kells range, indicating the early build-up of ice in the protection of its lee slopes.

5.6 GLACIAL ERRATICS TRAINS

The distribution of glacial erratics from five source rocks was mapped in the study area; these are considered separately below.

(1) The Loch Doon granite erratics train

The widespread distribution of the Loch Doon granite erratics over the western Southern Uplands and south Central Lowlands of Scotland has been referred to by many workers (A. Geikie, 1865; Forsyth 1892; Horne 1894; Smith 1898; Charlesworth 1926a; Richey *et al.* 1930; Simpson *et al.* 1936; Sissons 1964, 1967a Figure 29, 1976). Of these writers, however, only Charlesworth (1926a) attempted to describe in any detail the margins of the erratics train and their relationship to ice movement within the study area. He mentioned (p.4) that great numbers of granite boulders occurred on the summits of Merrick, Kirriereoch and Tarfessock, in the western part of the field area, and stated that this indicated a flow of ice from the east. The absence of boulders from the eastern flanks of Benyellary above 490 m was considered by Charlesworth to be due to the screening effect of the Merrick hills. To the south and SW of the granite outcrop Charlesworth described (p.5) the occurrence of granite blocks on the metamorphic rocks in Glen Trool and on the summits of Curleywee, White Hill and Lamachan, commenting that their emplacement indicated a considerable amount of uplift by ice. He also stated that " . . . no granite erratics surmounted Corserine, Meaul, Carinsgarroch, Meikle Millyea and Little Millyea, all in the Rhinns of Kells" (p.5) and suggested that this was because ice from the Kells was flanked by powerful glaciers that flowed on approximately parallel courses from

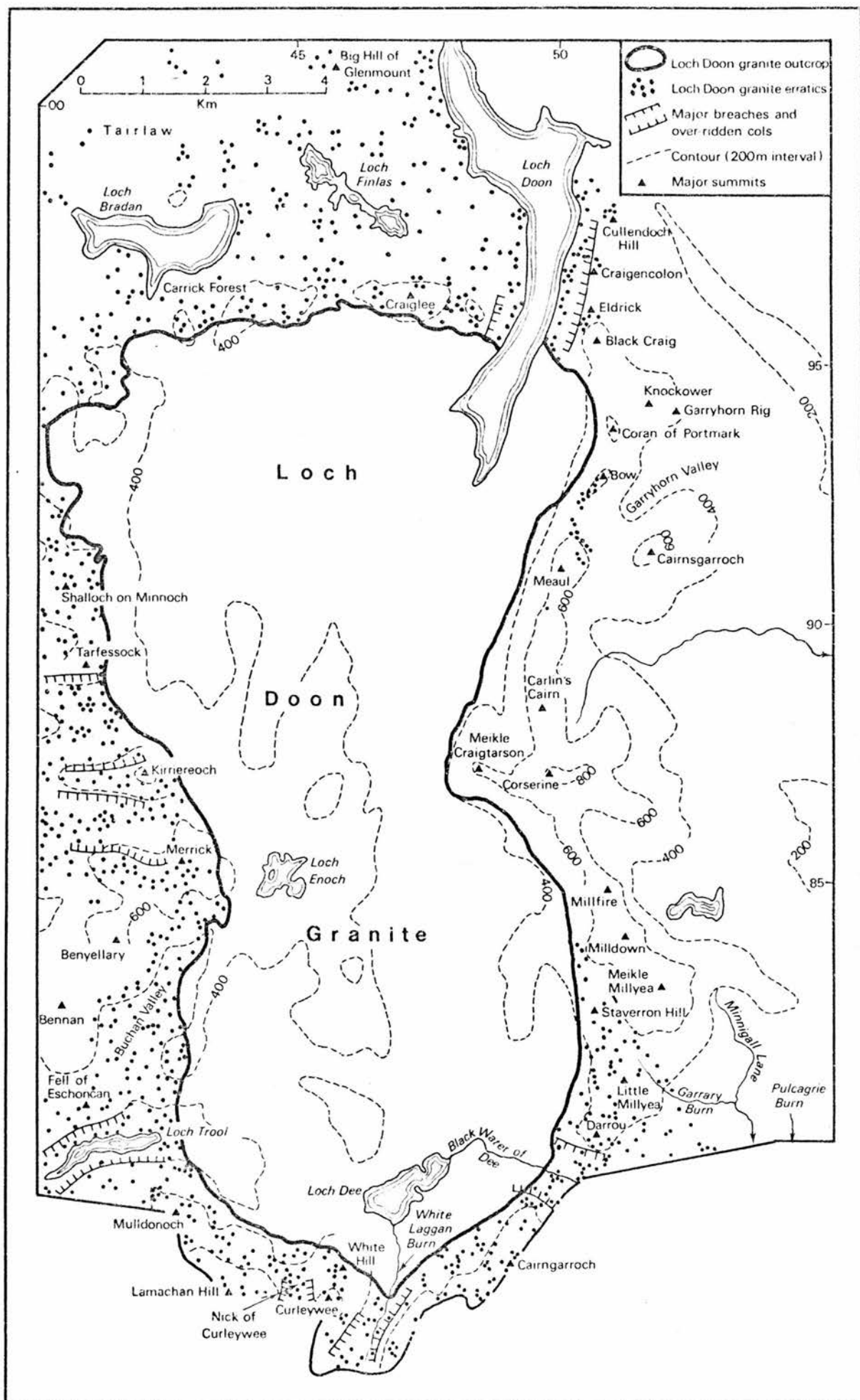
the area of Carsphairn. Moreover, he noted that they were only seen to have crossed the Kells range in the south, between the summits of Little Millyea and Darrou, whence they spread out to the SE along the valley of the Black Water of Dee. Finally, he commented (p.4) on their abundance over the country west of the shores of Loch Doon, but he did not attempt to define an eastern margin to the erratics train in this area.

The present writer has attempted to define the distribution of the Loch Doon granite erratics within the same area, but in more detail. The limited occurrence of stone walls on the hills surrounding the granite outcrop meant that the traverse method was used in the majority of observations made during the course of this mapping. All locations referred to in the text are related to Figure 5.3 unless otherwise stated.

The SE margin of the erratics train was located by Straverron Hill, which is adjacent to the granite/metamorphosed greywacke contact, at an altitude of 480 m. From here the limit was traced toward the SE to an altitude 610 m and through the col between the summits of Little Millyea and Meikle Millyea. Beyond the col, boulders occur sporadically in the valley of Garrary Burn where the margin, which is somewhat ill-defined at this point, becomes orientated NNW-SSE. This change in orientation is due, on the basis of striae evidence (Section 5.7 and Figure 5.7), to the influence of an ice stream emanating from the eastern side of the Kells range and flowing SSE. By Pulcagrie Burn it was impossible to map the margin, for extensive plantations of conifers cover the area. Systematic traverses were made to the north and NE of this line, covering the area by Milldown and Meikle Millyea summits and in the valley of Minnigall Lane, but

Figure 5.3

Distribution of Loch Doon granite erratics.



granite boulders were not encountered.

Granite boulders, some 4 m in length, occur extensively in the valley of the Black Water of Dee, on the slopes and floor of the Dee breach and on the summit of Cairngarroch (557 m); the latter implying uplift of some 180 m from the granite bedrock below. From the upper reaches of the glacially overdeepened White Laggan Burn and into the valley of the southward-flowing Pulnee Burn, granite blocks are strewn across the slopes and valley floors in great numbers, while to the west they occur abundantly on the summits of White Hill (596 m) and Curleywee (674 m) as well as in Curleywee corrie. The presence of granite erratics in the latter is partly explained by a small inlier of granite that crops out on its floor. However, boulders can be traced to the south, through the Nick of Curleywee breach and into the Penkiln Burn valley. Although the corrie is north-facing, the distribution of erratics suggests that at one stage, probably when the ice-sheet was well developed, ice flowed to the south into the corrie, over-riding its backwall to spread out into the lowland area beyond. This pattern is repeated farther west where great numbers of granite blocks cover the valley occupied by Shiel Burn. Here, the present stream has cut into thick till deposits in which are embedded well-rounded boulders of granite. Similarly on the summit of the Brishes (457 m) they are equally numerous, one block measuring 3.1 x 1.5 x 3.7 m. Immediately to the south and SE the summits of Mulldonoch (557 m) and Lamachan Hill (716 m) are littered with boulders up to 3 m in length. For their emplacement on the summit of Lamachan Hill, an uplift of basal ice from the granite bedrock below of the order of 400 m is indicated.

The widespread distribution of Loch Doon granite erratics on the summits and in the glacially overdeepened cols and valleys in the area between Black Water of Dee and Glen Trool, combined with corroborating evidence from the alignment of these landforms, provide unequivocal proofs of the former existence of a massive southerly flow of ice. Although the Glen Trool and Dee glacial breaches provided outlets for the ice, it is clear that they could not accommodate the larger volumes once the Loch Doon basin had become filled. Moreover, the occurrence of granite erratics on top of the highest summits in this area demonstrates that at one stage these hills were completely submerged by the ice-sheet.

Within the Glen Trool breach, objective assessment of the frequency of occurrence of granite boulders proved difficult to make owing to the very extensive conifer plantations. Numerous forest walks and Forestry Commission roads, however, provided a useful means of traversing certain parts of the area and thus a generalised picture was obtained.

At the SW end of Loch Trool granite erratics occur somewhat infrequently, but farther to the NE, as the metamorphosed greywacke/granite contact zone is approached, their numbers increase. An interesting feature of the boulders in this area, as well as of those mapped on Lamachan Hill, is their well-rounded nature so close to the source area. This contrasts with the observations made on the Norber erratics, which tend to show an increase in angularity toward the source area (Embleton and King 1975). On the north side of the Glen Trool breach granite blocks occur abundantly on Green Torr and Rig of Stroan, the summit of the Fell of Eschonan and in the valley

of the Buchan Burn. Above 460 m altitude in this area however, they become much less frequent, while at 500 m on Craigengashel summit and at 550 m on Bennan they are completely absent. This upper limit to the erratics can be traced north to the headwaters of Whitelands Burn and the Braes of Mulgarvie, which lie below Benyellary summit. Moreover, the summit of Benyellary (719 m) and its western slopes above 500 m are similarly devoid of granite boulders, even though striae and the glacially scoured nature of the summit provide evidence to indicate that these areas have been over-ridden by ice at one time.

Granite boulders are not encountered again until ca. 760 m altitude on the south face of Merrick. Here, they suddenly appear in great numbers, and their lower limit can be traced as a definite E-W trending line across the upper slopes of the hill. The summit of Merrick (843 m) is similarly littered with granite boulders (Plate I). The presence of these erratics has been referred to in the literature on numerous occasions (Horne 1894; Charlesworth 1926a; Sissons 1967a, 1978). They are largely sub-angular in shape and of various sizes, one block measuring 3.5 x 2.8 x 1.5 m being found less than 100 m from the summit triangulation point. The hills to the north of Merrick (which include Kirriereoch (782 m), Tarfessock (696 m) and Shalloch-on-Minnoch (768 m)) and the intervening E-W orientated troughs and cols are similarly littered with numerous granite erratics. However, three corries that are cut into the eastern flanks of Merrick and Kirriereoch are devoid of such erratics. Considering the extensive distribution immediately to the west, their absence in these three localities seems surprising. The implication of ^{this} apparent anomaly will be discussed in Chapter 13 with reference to the Loch Lomond Advance glacier limits.



Plate I: Loch Doon granite erratics on the summit of Merrick
(ca. 843 m O.D.).



Plate II: Tributary meltwater channel of channel 1
(Figure 7.1B).

Nevertheless, the general distribution of erratics in the Merrick range of hills confirms Charlesworth's (1926a) statement of a massive westerly flow of ice over the area originating from the Loch Doon basin. At the same time, this indicates a considerable uphill transport of erratics. Horne (1894) has drawn attention to this phenomenon and has estimated that uplift was of the order of 150 m in the case of Merrick summit; the highest point on the granite being at an altitude of 692 m. However, the granite bedrock to the east of Merrick summit averages 460 m in altitude, which suggests that Horne's estimate is low and that an uplift of around 400 m seems more realistic. Moreover, this implies that at times of extensive ice cover the basal layers of the ice-sheet moved uphill and over some of the highest peaks in the field area. For this to occur, the surface of the ice-sheet must have been situated at a considerably higher elevation than the highest granite erratics.

The absence of granite boulders on the summits of Bennan, Benyellary and the surrounding slopes above 460 m provides a good example of how ice-sheet movement was controlled, to some degree, by the underlying relief and not entirely by the shielding effect of Merrick summit, as suggested by Charlesworth (1926a). Two factors are of importance here.

- 1) The grain of the relief in the SW part of the Loch Doon basin is dominantly N-S (Figures 2.1, 5.1), as shown for example by the deep troughs of the Buchan and Gairland Burns. Thus here, the basal layers of the ice-sheet would have been confined to these troughs, giving little room for lateral spread until the ice became thick enough to over-ride the summits of

Bennan and Benyellary to the west. Even at this stage, it is probable that only the upper layers of the ice-sheet would be affected. Farther north, by Loch Enoch the relief is relatively more "open" and therefore exercised less control on the direction of ice movement.

- 2) The metamorphosed greywacke/granite contact zone is located on the floor of the Buchan Burn trough at ca. 300 m altitude. This is more than 400 m below the summit slopes of Benyellary. This considerable difference in altitude combined with the fact that at this point the basal ice (controlled by the relief) was flowing parallel to the metamorphosed greywacke/granite contact, created little opportunity for the granite erratics to be spread in a westerly direction. In contrast, farther north, the contact zone follows the base of the east-facing cliff-line of the Merrick range, lying at right-angles to the direction of ice movement. Consequently the spread of boulders to the west is considerable in the latter area.

To the north and NW of the Loch Doon granite outcrop, boulders occur in great numbers over the area now occupied by the Carrick Forest, by the shores of Lochs Bradan and Finlas and within the cols that traverse the range of hills to the east of Tairlaw. By the western shores of Loch Doon and on Craiglee well-rounded granite blocks up to 4 m in diameter are common and can be clearly traced north, over the Big Hill of Glenmount to Dalmellington.

On the eastern shores of Loch Doon, the presence of a second granite erratics train related to the Cairnsmore of Carsphairn intrusion made the mapping of the northern part of the eastern margin of the

Loch Doon erratics train impossible (Figure 5.4). This is because in the hand specimen the two are virtually indistinguishable. Hence where the two margins were seen to merge, no attempt was made to separate them. A careful search for Loch Doon granite erratics on Garryhorn Rig, which lies to the east of the Kells range, proved negative and similarly with traverses made across the slopes and summit of Knockower and the flat peat-covered col lying between the latter and Coran of Portmark. It is possible, however, that this extensive area of peat bog may conceal erratics below. This suggestion is supported by the occurrence of fine-grained granite boulders (from the contact zone) within a stone wall at an altitude of 445 m, implying that ice flowed NE through the col between Coran of Portmark and Black Craig and into the Carsphairn Lane valley. Traverses made along the western slopes of Coran of Portmark and Black Craig encountered granite erratics only below 300 m. The several large blocks of granite " . . . perched on the steep hillside at an elevation of 1400 feet" on the west side of the Loch Doon breach described by Forsyth (1892, p.385) were not located, even after a very extensive search. Farther north between Black Craig and Eldrick Hill (NX 505958) seven extremely angular granite boulders were mapped at ca. 360 m altitude, one measuring 2.5 x 1.2 x 0.5 m. Six occur in and to the west of the col, whilst one was found on the eastern side at an altitude of 335 m. The presence of these erratics again suggests that ice crossed the northern part of the Kells range.

The hills of Craigencolon and Cullendoch farther north are littered with granite erratics that probably have their provenance in the Loch Doon basin. This evidence in itself is inconclusive, however,

for immediately east of this area, the Cairnsmore of Carsphairn erratics train overlaps with that one emanating from the Loch Doon basin (Figure 5.4). This area is considered separately below. Although the margin of the Loch Doon erratics train is difficult to define specifically in this area, there is strong evidence to suggest that ice from the basin did cross the Kells range north of Coran of Portmark, making use of the cols between each of the summits.

Further traverses were made to the south of Coran of Portmark summit in order to determine whether ice had crossed the Rhinns of Kells at any other points. Granite erratics were not encountered in traverses made along the summit and eastern flanks of the Coran of Portmark. However, 1 km south, 25 sub-angular granite blocks occur on the summit of Bow at an altitude of 610 m and 12 more in the col between Bow and Meaul at 560 m (Figure 5.4). The eastern termination of the stone wall rising from the valley of the Garryhorn Burn to the same col was found to contain many more, some measuring 1.5 m in length. On Meaul summit granite boulders are again absent, but on its NE slopes 18 were mapped (Figure 5.4). A careful search of the col between Meaul and Cairnsgarroch, the latter's summit area and the east and SE slopes of Meaul produced negative results, although at an altitude of 620 m in the col between Meaul and Goat Crag (NX 496904) one small fine-grained granite boulder was located. Finally, the western and eastern slopes of the Rhinns of Kells between Carlin's Cairn and Milldown (including the broad summits of Meikle Craigtarson, Corserine and Millfire) were traversed but no Loch Doon granite erratics were encountered.

Evidence collected from the Rhinns of Kells confirms, in part,

Charlesworth's (1926a) conclusions but other aspects remain questionable. The presence of granite erratics by Loch Doon in the north of the range and on the southern face of Meikle Millyea in the south supports his suggestion of ice flow away from an ice-shed. Further, the absence of granite boulders from a 9 km stretch of ground between Goat Crag and Meikle Millyea implies that the ice-shed lay in this zone, and linking with that over Merrick summit.

However, there is unequivocal evidence to indicate that ice crossed the Rhinns of Kells, for granite erratics are found to the east of the range by Black Craig in the north and Little Millyea in the south, where the influence of relief on basal ice flow exercised less of a control. Further, in the latter area, boulders mapped at 610 m indicate that ice from the Loch Doon basin crossed the Kells range at a level ca. 160 m higher than that stated by Charlesworth. The occurrence of numerous granite blocks on the summit of Bow and the NE face of Meaul implies that basal ice from the Loch Doon basin must have reached an altitude of at least 610 m and that its surface must have been a great deal higher. This evidence points to the conclusion that Loch Doon ice at least topped the central-northern section of the Rhinns of Kells, a point not commented on by Charlesworth.

There is no evidence to suggest that ice from the Loch Doon basin actually spilled over the central part of the Rhinns of Kells and into the Polmaddy, Garryhorn and Polharrow valleys to the east. Granite boulders from the Loch Doon intrusion are absent from these areas. This absence is only explained in part by the occurrence of Loch Lomond Advance glacier limits in the headwaters of the two latter valleys. These limits can be taken to show glacier distributions

analogous to those that existed during the growth of the later ice-sheets that covered the area. Such ice accumulations may well have prevented significant (or any) transfluence of Loch Doon ice into these valleys.

In summary, the evidence provided by the mapping of the distribution of Loch Doon granite erratics indicates the following.

- 1) A broadly radial flow of ice from the Loch Doon basin (except in the east), confirming the previously held opinions that the area was a major ice accumulation centre in the Southern Uplands during the Late-Devensian ice-sheet phase.
- 2) An ice-shed was present, which at the time of maximum ice-sheet development extended from the Merrick area in the west to Corserine in the Kells range, probably via the major summits of Mullwharchar and Meikle Craigtarson.
- 3) The whole area was, at one stage, completely submerged by a single ice dome. The occurrence of granite boulders on most of the highest summits in the area (e.g. Merrick, Kirriereoch, Tarfessock, Lamachan and Curleywee) appears to permit no other reasonable conclusion.
- 4) In certain areas the underlying relief exercised considerable control, especially during the early stages of ice-sheet build-up, on the direction of ice movement and the emplacement of granite boulders.

(ii) The metamorphosed greywacke erratics train

No mention has been made in the literature regarding the occurrence, if any, of metamorphosed greywacke blocks resting on the Loch Doon granite. It appears that all previous studies have tended

to look solely at the outward spread of granite erratics from the basin onto the surrounding metamorphics. This approach was used initially and the results have already been outlined. It was decided subsequently to test this apparently simple radial relationship by traversing the granite outcrop in search of greywacke erratics.

Three* areas were located where this reverse situation held, each occurring toward the western margin of the granite outcrop between Loch Enoch and Loch Slochy (Figure 13.2). Moreover, all were found in association with a series of till mounds, and on no occasion were greywacke boulders seen resting directly on granite bedrock. In the first area, numerous erratics, averaging 2 m in length, were mapped in the valley of Caldron Burn and on the Rig of Munshalloch at ca. 500 m O.D. In places these were situated 1.5 km from the granite/meta-morphosed greywacke contact. Closely spaced traverses showed that their distribution terminated abruptly and did not "fade". In certain parts, the margins coincide with well-defined drift limits, as for example NW of Loch Enoch (Figure 13.2).

The second area of greywacke boulders occurs 1 km NE of Kirriereoch summit in the headwaters of the Tunskeen Lane valley and on the Castle-on-Oyne ridge at ca. 460 m O.D. Finally, 14 greywacke boulders, as well as numerous granite blocks, were mapped on the crest and slopes of a single, elongated ridge located by the ruins

* A fourth area was also located, but the greywacke blocks are here associated with a large landslide that has descended the east-facing slopes of Tarfessock. This feature is fully described in Chapter 13.

of Slaethornrig Farm. The ridge is 2 m high, 350 m long and orientated NE-SW. Small sections in the ridge flanks revealed a very sandy till. Despite an extensive search of the area adjacent to the ridge, greywacke boulders were not encountered.

The limited distribution of the greywacke boulders is paradoxical, for the Loch Doon granite boulders mapped on the hills of the Merrick range and in the headwaters of the River Cree indicate a westerly movement of ice, while the greywackes on the granite in turn show an easterly flow. Several possible explanations of this distribution must be considered:-

- 1) The boulders were soliflucted down the slopes of the Merrick hills into the granite basin below. However, this would not explain their limited occurrence solely on the western side of the granite outcrop. Furthermore, their presence up to 1.5 km from the granite/metamorphosed greywacke contact zone precludes any derivation by solifluction from the Merrick range.
- 2) It is possible that the boulders were deposited during the deglaciation of the ice-sheet by a late-stage movement from the Merrick range into the Loch Doon basin. As mentioned above, however, evidence suggests that the basin was a vast ice accumulation area during the Late-Devensian period. It seems difficult to envisage the extensive ice wastage in the basin required to enable ice to flow from the Merrick range and in effect to reverse completely the regional trend of former ice movement.
- 3) The boulders may be xenoliths of greywacke rocks that were

caught up in the granite during its emplacement and have subsequently weathered out. If this is so, it fails to explain their association solely with the till deposits and their limited distribution around the margins of the Loch Doon granite outcrop.

- 4) The limited and somewhat lobate occurrences of the areas of greywacke boulders may be explained in terms of a Lateglacial advance of ice from the corries on the eastern flanks of Merrick and Kirriereoch. This interpretation is supported by their distribution in relation to the corries and by the occurrence in every corrie in the Merrick area of evidence for the existence of such an advance. The implication of this point will be discussed further in Chapter 13 with respect to the distribution of Loch Lomond Advance glaciers.

(iii) The Cairnsmore of Carsphairn granite erratics train

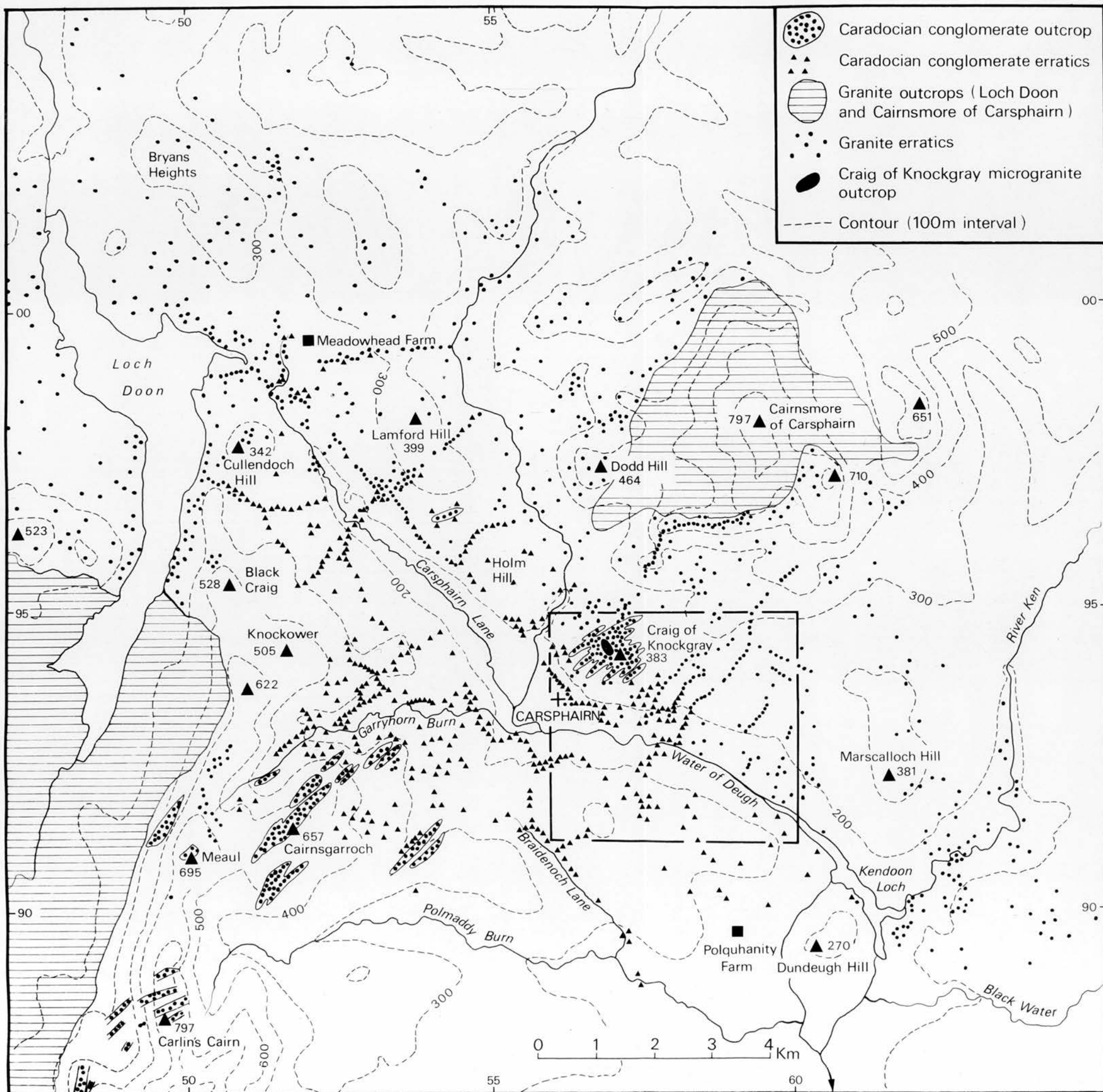
The major part of the Cairnsmore of Carsphairn granite erratics train lies outside the study area, but Skae *et al.* (1877) and Charlesworth (1926a) have described, in general terms, the distribution of granite boulders on the eastern margins. Skae *et al.* commented on the numerous blocks of Cairnsmore granite in the River Ken valley north of Smeaton Bridge, and in the valleys of its tributaries, while to the SE on the hills of Stroanpatrick, Culmark and Fingland, they were present in lesser numbers. Charlesworth (1926a) largely reiterated the work of Skae *et al.* (1877), but also mentioned their occurrence in the Carsphairn Lane and Water of Deugh valleys to their confluence with the River Ken. To the SE of the Ken, they were not encountered. Farther north, Charlesworth noted that the erratics could be clearly traced toward Dalmellington where they merge with the

stream of granite boulders originating from the Loch Doon basin. He concluded that their distribution over a relatively narrow belt of country was due to the granite outcrop lying astride an ice-shed from which glaciers flowed on more or less parallel courses, thus inhibiting any lateral spreading.

The distribution of Cairnsmore of Carsphairn granite erratics (Figure 5.4) covers an area that is more suited to agriculture and therefore stone walls form a major feature in the present landscape. As such, these provided a useful source for locating erratics. Each wall in the Carsphairn Lane - Water of Deugh - River Ken valley was traversed and the location of granite boulders marked on the 1:25,000 Ordnance Survey sheet. Continuity in the mapping was maintained by making traverses across the intervening fields.

No Cairnsmore granite erratics were encountered in traverses made in the River Ken valley south of its confluence with the Black Water. Immediately north, however, the margin of the erratics train was clearly defined. Large and very well-rounded boulders occur by Arnderroch Farm and the High Bridge of Ken in association with well-developed valley-fill deposits. Farther east, the margin lies along a range of E-W orientated hills (including Culmark Hill and Fingland Hill). The SW margin of the Cairnsmore granites can be traced between Craig of Knockgray and Marscalloch Hill as lying approximately along the present valley axis (Figure 5.4). On the SW banks of the Water of Deugh river granite boulders are only very rarely encountered, a total of three having been mapped, while on the NE side they occur more frequently, lying on and incorporated within the cross-valley ridge landforms. By Carsphairn village the margin becomes indistinct,

Figure 5.4 Distribution of Cairnsmore of Carsphairn and
Loch Doon granite and Caradocian conglomerate
erratics. Rectangle covers the area shown
in Figure 5.5.



as a large debris fan occupies the centre of the valley (Figure 7.8A). This fan is littered with Cairnsmore of Carsphairn boulders that have been carried down by the Water of Deugh and its tributaries, which find their origin within the granite outcrop. To the east of the fan, the slopes of Craig of Knockgray and the Benloch Burn valley are covered by numerous granite boulders, one that occurs on the southern slopes of Craig of Knockgray measuring $1.5 \times 1.0 \times 0.5$ m. Furthermore, sections in till deposits in the two above-mentioned areas contain similar sizeable granite erratics.

North of the Water of Deugh - Carsphairn Lane confluence, the eastern limit of the erratics train seems confined to the lower slopes of Holm Hill and Brockloch Craig. This line is an approximation, for the distribution of granite boulders in this area is somewhat sporadic. For example, an extensive search across Holm Hill encountered no erratics, while only 1 km to the NW 188 were located in a 220 m length of stone wall. No granite erratics were encountered on traverses made along the SW slopes of the Carsphairn Lane valley, south of Lamloch Farm. However, north of Lamloch great numbers suddenly appear and boulders occur on both sides of the valley. This increase can be partly explained by the incursion of Loch Doon granite erratics into the valley and their overlapping with those derived from the Cairnsmore of Carsphairn mass (Figure 5.4). North of this point the separation of the two erratics trains becomes impossible. Thus the provenance of the granite erratics that litter the drumlins in the vicinity of the Eriff Burn is difficult to establish. The same applies to the boulders found in association with an esker and a series of flat-topped kames, on the watershed of

the Carsphairn Lane by Meadowhead Farm. Granite boulders mapped by Loch Muck, on Byran's Heights and embedded in till deposits that form part of the walls of a deep gorge extending from Glen Muck to Dalmellington are again impossible to separate in terms of their source.

In summary, the SE margin of the Cairnsmore of Carsphairn granite erratics train has a very linear form and is orientated NW-SE. To the east of Dundough Hill the limit changes direction to become aligned W-E. To the north the limit is impossible to trace due to the interaction of Loch Doon ice with that derived from the Cairnsmore area. The distribution of boulders generally confirms Charlesworth's observations and supports his view that the ice ^{streams} in this valley had a strong linear component. However, the sudden change in the orientation of the margin by Dundough Hill suggests that this parallelism was not a constant feature throughout the valley and that the influence of ice streams emanating from the eastern slopes of the Kells range served to alter this trend in places. Furthermore, the distribution of Cairnsmore granite erratics both to the NW and SE of the outcrop indicates that the ice-shed described above as extending across the Loch Doon basin may also have continued across the Carsphairn Lane - Water of Deugh valley, possibly via Craig of Knockgray to Cairnsmore of Carsphairn summit.

(iv) The Caradocian conglomerate erratics train

The distribution of conglomerate erratics in the Carsphairn Lane - Water of Deugh valley has not been mapped previously and no mention of their use in tracing former ice movement has been made in the literature. It was decided to map their distribution at 1:25,000

scale with a view to establishing the direction and efficacy of ice movement from the eastern side of the northern Rhinns of Kells and to supplement evidence already obtained from the mapping of Cairnmore of Carsphairn granite erratics in locating the position of the former ice-shed in the Carsphairn area. This exercise proved successful for the area to the north and NW of the outcrops; however, to the south and SE, extensive plantations of coniferous trees made this work difficult and in places impossible. Thus, the distribution pattern south of Polmaddy Burn is incomplete.

As can be seen from Figure 5.4, the bedrock exposures of Caradocian conglomerate occur in two separate localities on each side of the Carsphairn Lane - Water of Deugh valley. It was found impossible to distinguish between these two in the hand specimen and consequently it was necessary to map the erratics as a single train.

Despite careful searches, conglomerate erratics appear to be absent from the area to the south of the Black Water and from the valley of the River Ken above its confluence with the Water of Deugh. They are first encountered on the northern slopes of Dundegh Hill and by Carminnow Farm, where their distribution is very sporadic and their size usually less than 1 m. NW of Dundegh their numbers increase, but their distribution is confined to the area SE of the Water of Deugh. This suggests that the NE margin of the erratics train at this point lies along the axis of the valley. However, 1 km SE of the Craig of Knockgray outcrop, conglomerate boulders suddenly appear on the NE side of the valley, where they are found in association with the cross-valley ridges. Closer to the bedrock exposures, the boulders measure up to 2.5 m in length and are very angular in shape.

NW of Craig of Knockgray the NE margin of the erratics train is difficult to plot with any accuracy, for the distribution of boulders is sporadic. Conglomerate blocks occur on the NE slopes of Holm Hill, Brockloch Bennan and Lamford Hill, but not apparently on the slopes of Dodd Hill and Wee Meaul, which lie to the east of the Water of Deugh. Their absence here is probably due to the influence of ice streams flowing SW from the Cairnsmore of Carsphairn region. Farther north, the boulders become much smaller in size, averaging only 0.5 m in length, while beyond Meadowhead Farm, they are absent.

On the SW slopes of the valley, due largely to the greater size of the bedrock exposures, conglomerate boulders are distributed in prodigious numbers in the valleys of the Braidenoch Lane, Halfmark Burn and Garryhorn Burn. This is particularly so across the mouths of the Halfmark and Garryhorn Burns at their confluence with the Water of Deugh. Here, conglomerate erratics occur in large numbers in the fields and stone walls and are characteristically very angular in shape and measure up to 2 m in length. To the SE, however, their numbers and size diminish rapidly such that within 1.5 km they are only occasionally encountered. Unfortunately, as mentioned above, it was found impossible to trace any definite margin to the erratics in this direction owing to extensive afforestation, although conglomerate erratics were found occasionally in the valley of Polmaddy Burn. To the north of these outcrops a western margin to the erratics train was mapped along the lower slopes of Knockower and Black Craig to Cullendoch Hill at ca. 380 m altitude (Figure 5.4). East of this line, the slopes of Carsphairn Lane valley are littered with conglomerate boulders, but they decrease rapidly in number

towards the NW, none being found to the north of Cullendoch Hill. In addition conglomerate erratics were not encountered in traverses made along the Rhinns of Kells north of Carlin's Cairn.

The evidence presented suggests that the distribution of conglomerate erratics in the Carsphairn Lane - Water of Deugh - River Ken valley is limited, despite the relatively extensive bedrock outcrops, and that they rapidly decrease in both number and size away from the outcrops. Although no quantitative analysis was made of this latter aspect, it is possible to make certain inferences from the evidence collected. The massive nature of the conglomerate rocks coupled with the fact that they have undergone thermal metamorphism has made them resistant to erosion. Consequently they cap some of the highest summits in the northern Rhinns of Kells (i.e. Carlin's Cairn (795 m), Meaul (695 m) and Cairnsgarroch (657 m)). Thus it is difficult to explain their rapid decrease in numbers away from the outcrops solely in terms of disaggregation or dilution. A limited distribution pattern to the Craig of Knockgray microgranite erratics train was also found in the same area, and therefore the implications of the restricted distribution of conglomerate erratics is considered in that section (see below).

Their distribution does, however, reveal the presence of a former ice-shed zone in the area, which probably lay between Cairnsgarroch and Craig of Knockgray. The fan-like spread of conglomerate boulders from bedrock exposures by Cairnsgarroch and Craighit to the north, NE, east and SE supports this interpretation. The distribution of boulders to the NW and SE of the outcrop capping Craig of Knockgray also provides corroborating evidence. Finally, as with the Cairnsmore of Carsphairn

granite erratics train, the conglomerates are confined to a narrow and linear band of country, which implies that the glaciers were competing for space in the valley thus mitigating against lateral spreading of ice, and therefore erratics, in this area.

(v) The Craig of Knockgray microgranite erratics train

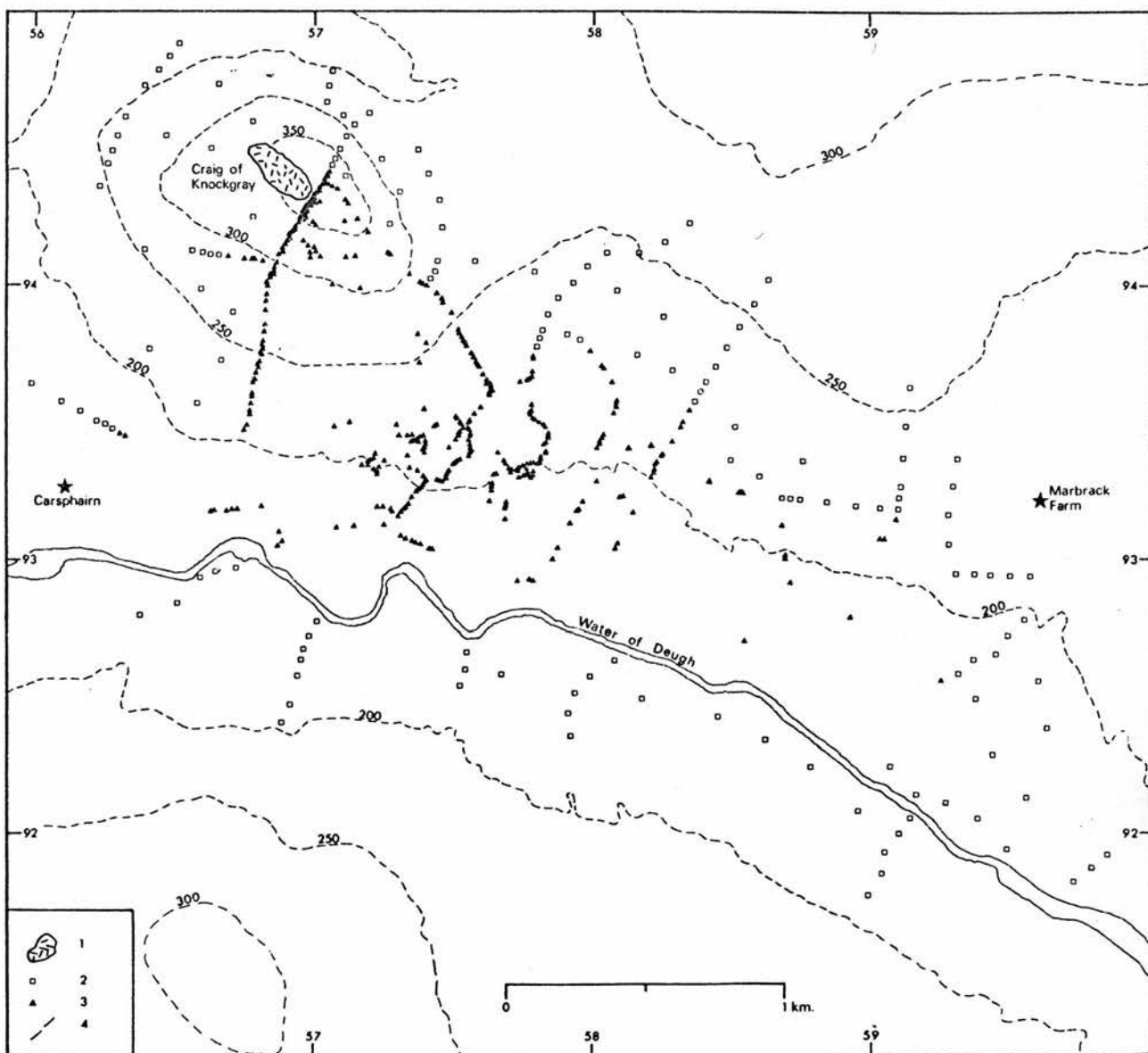
The outcrop of microgranite, which is probably an inlier of the main Cairnmore of Carsphairn granitic intrusion, is located immediately NW of the summit of Craig of Knockgray, the actual summit point being composed of thermally metamorphosed Caradocian conglomerates (Figure 2.2). The outcrop is very limited, covering an area of *ca.* 0.033 km^2 .

The distribution of boulders from this limited source was mapped in order to complement studies made of the conglomerate erratics train. As the outcrop is small, very closely spaced (20 m interval) traverses coupled with detailed examination of every metre of dry stone wall, were carried out on Craig of Knockgray and surrounding areas. Where a stone wall rests on till deposits, the stones within it may be regarded as a representative sample of glacially transported material of a certain size range (Morrissey and Romer 1973). Since the microgranite has never been quarried, any of these erratics in the walls may be assumed to have been derived from the surface of neighbouring fields. In addition, all till sections in the area were examined for microgranite boulders.

A total of 2,758 microgranite erratics was identified and the location of each was plotted on the 1:10,560 Ordnance Survey map. Figure 5.5 shows this distribution: each black triangle indicates

Figure 5.5 Craig of Knockgray microgranite erratics train
(see Figure 5.4 for location);

1. Microgranite outcrop;
2. Areas traversed but no erratics found;
3. Microgranite boulders per metre of dry
stone wall;
4. Contour (50 m interval).



the presence of at least one microgranite boulder in that metre section of wall as well as single boulders found in the intervening fields and in the till sections. The hollow squares record areas that were mapped but where no microgranite erratics were encountered.

The overall distribution pattern of the microgranite erratics is triangular, the apex lying SE of the outcrop. The farthest-travelled boulder that was mapped occurs in a stone wall by Marbrack Farm (NX 597933) only 2.8 km from the source, despite extensive searches made up to 15 km both NW and SE of the outcrop. At least 80 per cent of the erratics occur within 1.25 km of the source and all are confined to the northern side of the Water of Deugh river. Similarly, as noted above, the Caradocian conglomerate erratics train has a clearly defined linear path in the Carsphairn Lane - Water of Deugh valley as well as showing a limited distance of transport, they not being found NW of Meadowhead Farm (Figure 5.4).

In a small-scale study such as this the influence of man in moving boulders downslope for wall construction has to be borne in mind. Yet it is unlikely that stones would have been carried more than short distances, especially as wall building was normally paid for by the yard. Downslope movement of boulders by gliding under periglacial conditions of the Loch Lomond Stadial may also have affected the distribution of erratics. However, the abundance of erratics on the high and often steep parts of Craig of Knockgray implies that such movement was limited. Furthermore, some of the southernmost erratics, near the Water of Deugh, occur on mounds and hence cannot have reached their present positions by gliding. It is therefore concluded that, although slight displacement of some erratics may

have occurred, the distribution shown in Figure 5.5 reflects former ice movement in the Carsphairn area. Several interesting points are revealed by this pattern.

- 1) The erratics occur only on the south and SE slopes of Craig of Knockgray (Figure 5.5). This implies that the ice that covered the hill and distributed the erratics flowed towards directions between south and SE. However, evidence presented on the distribution of conglomerates from the same hill shows that ice flowed both to the SE and NW in this area. Such distributions therefore allow the former ice-shed to be accurately located in this section of the valley as lying just to the NW of Craig of Knockgray (Figure 5.8).
- 2) The relative narrowness of the train of microgranite boulders confirms the observations made on the distribution pattern of the Cairnsmore of Carsphairn granite and Caradocian conglomerate erratics in the same area, which demonstrated clearly defined, linear paths of ice flow along the Water of Deugh valley axis.
- 3) The major trend of the microgranite erratics train shows that the ice flowed parallel to the Water of Deugh valley axis, which is perpendicular to the orientation of the cross-valley ridges. Evidence that the ice that distributed some of these erratics was associated with the formation of the cross-valley ridges is provided by their occurrence within the olive till deposits of which the ridges are composed.

Classic erratics train patterns tend to be aligned in the direction of ice transport with values representing erratic frequency

declining both in a down-ice direction and perpendicular to it (e.g. G. Lundqvist 1935; Dreimanis 1958, 1958; Gillberg 1965; Wennervirta 1968; Shilts 1973a, b; Shakesby 1978a). The Craig of Knockgray erratics train, however, shows two features that conflict with this general pattern.

- 1) The microgranite erratics have a restricted distribution, for the train extends for only 2.8 km. Although the outcrop is of limited extent this does not entirely explain this distribution. For example, the Lennoxton essexite outcrop in the Central Lowlands of Scotland has a surface exposure only 200-300 m in diameter, yet Peach (1909) found individual boulders some 60 km from the source and Shakesby (1978b) recorded an uninterrupted distribution of essexite boulders for 20 km east of the outcrop.
- 2) The erratics train subtends the unusually large angle of $ca. 90^{\circ}$ (Figure 5.5). If ice carrying the microgranite erratics flowed continuously towards the SE, then it would have been expected to have streamlined the erratics in this direction (cf. Nichol and Bjorklund 1973; Shilts 1977; Shakesby 1978a, b).

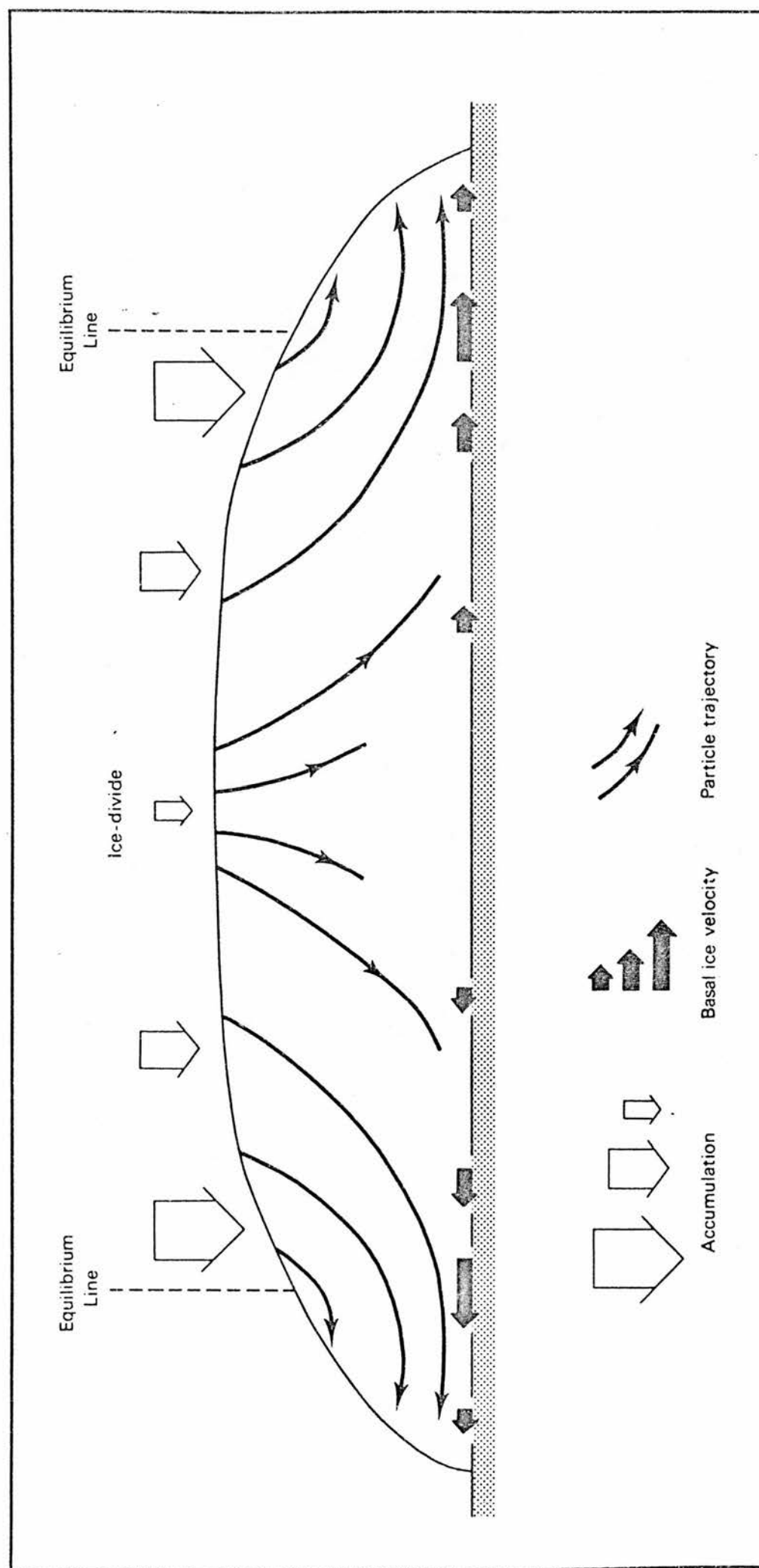
The first above-mentioned anomaly necessitates consideration of the time of emplacement of erratics and till in the area. The distribution of Loch Doon and Cairnsmore of Carsphairn granite and Caradocian conglomerate erratics (Figures 5.3 and 5.4) indicates that an ice-shed existed in the study area during the Late-Devensian maximum (Figure 5.8). In an ice-shed situation ice movement occurs by sheet flow, which may take the form of internal creep alone or may also involve basal shearing (Nye 1959). As it does so, there is

a strong vertical component as individual particles of ice are covered by subsequent accumulation (Budd et al. 1971). This vertical component has also been referred to by Paterson (1969), Schytt (1974) and Embleton and King (1975, p.288), who state that after the establishment of an ice-divide zone there is very little horizontal ice movement, the ice moving vertically down towards the basal areas. As a result basal ice velocities will be very low in this zone (Figure 5.6) and the capacity for ice to erode, virtually eliminated (Boulton 1974).

Given these conditions it appears impossible for the vast quantities of till present in the vicinity of the former ice-shed by Carsphairn to have been deposited when the ice-shed existed (see Chapter 7). Hence conditions pertaining before the ice-shed came into existence require consideration. Initial ice movement in the Carsphairn area appears to have been from the hills located to the west and east of the Carsphairn Lane - Water of Deugh valley. This view is supported by Loch Lomond Advance glacier limits in the valley occupied by Garryhorn Burn, only 4 km west of Carsphairn village (Figure 13.1), as well as those described by Holden (1977) from the Cairnsmore of Carsphairn hills to the NE. These limits may be regarded as portraying a stage in ice-sheet growth (cf. Sissons 1979b). In accord are the presence of Cairnsmore of Carsphairn granite erratics in the Carsphairn area (Figure 5.4) as well as the Caradocian conglomerate erratics train emanating from the Garryhorn valley.

The opposing flow directions of these two ice masses along with the relief control exercised by Craig of Knockgray hill would have led to stagnation or reduction of ice movement in this area. The subsequent development of the ice-shed would have preserved the

Figure 5.6 Schematic diagram of an ice-sheet showing
distribution of snow input and related flow
characteristics (modified after Sugden and
John (1976)).



erratics and till debris thus emplaced. Such an arrangement is demonstrated by the microgranite erratics train terminating only 2.8 km from its source as well as the limited transport of conglomerate erratics in the same area. Similar observations have been made by Ahlmann (1938), G. Lundqvist (1940) and Gillberg (1965), while Mutanen (1971, p.138) suggested that "relict (boulder) fans may have been preserved in favourable places, as where stagnation has prevailed during subsequent phases of movement".

This hypothesis also allows the second anomaly mentioned above to be explained. Initial ice flow from the Cairnsmore of Carsphairn hills implies that the original distribution of microgranite boulders was in a southerly direction from the outcrop. Subsequently, SE movement of ice spread these erratics a limited distance down-valley (Figure 5.5). That many erratics still remain on the south side of the outcrop is also in accord with the hypothesis since this area is virtually at the former ice-shed and ice flow would have been negligible.

This interpretation has implications for the stage at which the cross-valley ridges were formed, and these will be discussed in Chapter 12.

5.7 GLACIAL STRIAE

The assumption made in interpreting the striae mapped in the study area is that all are related to the movement of the last ice-sheet except those found in localities where Loch Lomond Advance glaciers are considered to have existed. However, Virkkala (1960)

has emphasised that great caution must be used in the interpretation of striae. He suggested that if any validity is to be attached to the results, studies must be based on a very large number of striae observations over a reasonably large area and other evidence of ice movement should be taken into consideration, particularly the distribution of erratics. Clearly, bedrock irregularities can produce considerable local variations in basal ice movement, which may differ from the movement of the main bulk of the ice above, and during changes in ice thickness, especially during deglaciation, directions of ice movement as a whole may alter.

Bearing these points in mind, it is convenient to discuss the evidence of ice movement from glacial striae by considering their distribution in two areas, namely

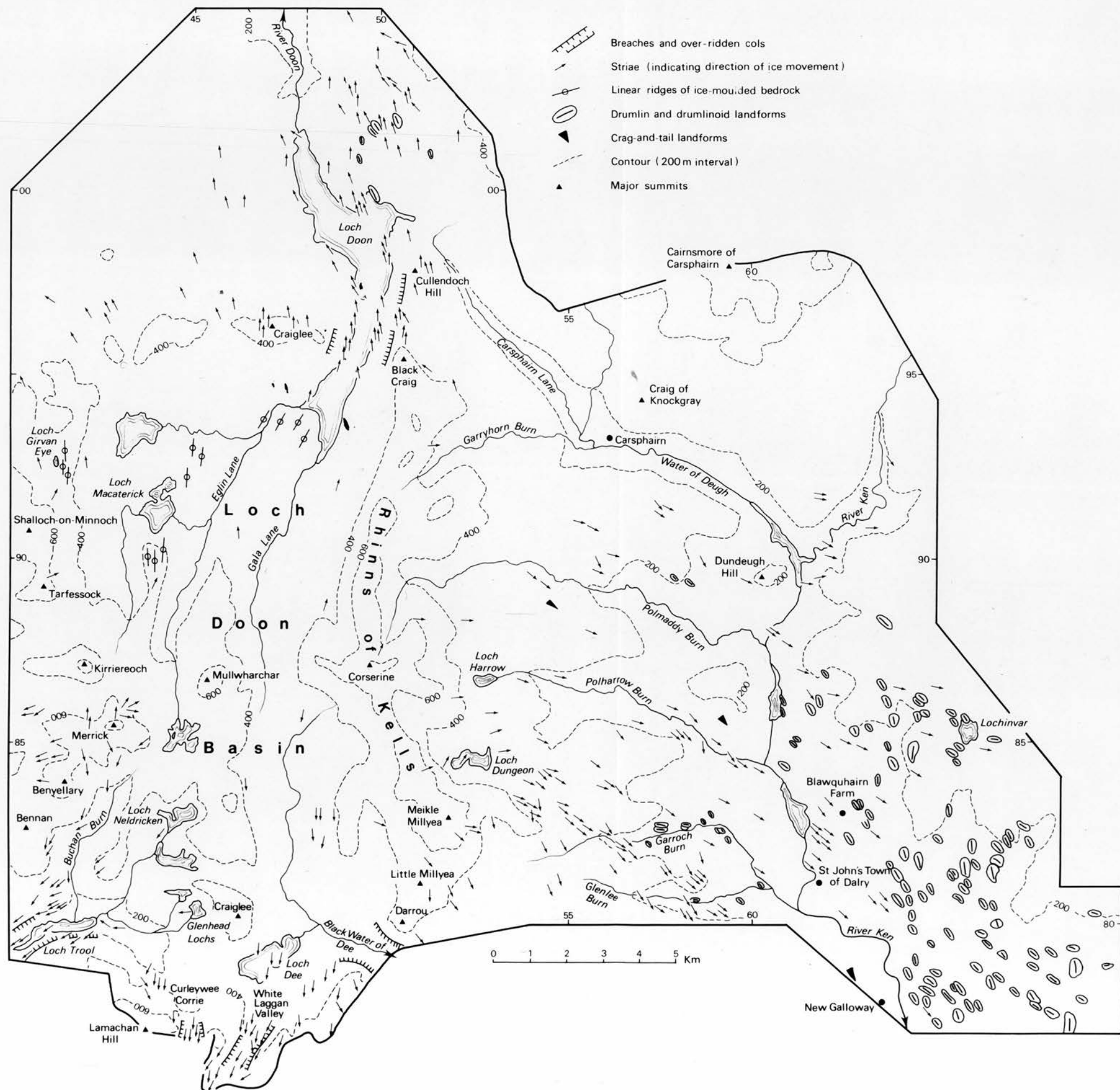
- 1) the Loch Doon basin and surrounding uplands; and
 - 2) the Carsphairn Lane - Water of Deugh - River Ken valley.
- 1) The Loch Doon Basin and surrounding uplands.

In general, the distribution of striae on the granite outcrop is somewhat sporadic (Figure 5.7). However, where recorded they have an almost universal north or south orientation, implying a linear flow away from the ice-shed inferred above. Exceptions to this pattern occur by Loch Neldricken and the Round Loch of Glenhead where basal ice flow was controlled by the trend of the underlying relief. A similar situation occurs by Loch Doon, where striae tend to converge on the breach that cuts through the metamorphic aureole.

On the surrounding uplands of hard metamorphic rocks, striae are extremely well developed and tend to mirror the patterns of ice movement established from mapping the distribution of granite erratics

Figure 5.7

Striae and ice-moulded landforms of the
W-C Southern Uplands.



and the orientations of over-ridden cols and glacial breaches. Ice-scoured bedrock covered with numerous striae abounds within the breaches of Glen Trool and Loch Doon as well as in the cols in the backwall of Curleywee corrie (at 590 m) and the head of White Laggan Burn (at 430 m). There is an absence of striae from the Dee breach, which is largely due to the till deposits that mantle its walls.

Striae orientated E-W occur at 600 m on the western slopes of Benyellary summit and in the valley head of Kirkennan Burn between 530 and 610 m (Figure 5.7). This implies that the summit has been over-ridden by ice, but as mentioned previously there is an absence of granite erratics from this area. However, this apparently anomalous situation, linked with the evidence and discussion presented in Section 5.6, may be resolved by considering the orientations of the striae developed in the Buchan valley trough, which lies immediately to the SE. Here, the major trend of the striae is NE-SW indicating a strong flow of basal ice in this direction, controlled by the alignment of the trough. Further, this implies that a flow of ice to the west could only have occurred at a later stage when the ice-sheet had built up sufficiently to over-top the western wall of the Buchan trough (some 360 m high) and ultimately the summit of Benyellary itself.

Nine sets of striae were recorded in the two corries cut into the NE face of Merrick summit. One of these sets is at an altitude of 760 m on the corrie backwall, which is the highest found within the field area. Their orientation SW-NE and W-E combined with evidence from greywacke erratics, which lie on the granite immediately to the NE of the corrie, suggest ice flow from these corries into the Loch Doon basin during the Loch Lomond Advance.

Glacial striae are very sparsely represented on the summits and western slopes of the Rhinns of Kells as these tend to be well vegetated, which masks the underlying bedrock. The striae evidence is therefore insufficient to establish ice movement directions in the greater part of this hill range. Striae do occur, however, up to an altitude of 610 m on the SE slopes of Meikle Millyea. These trend NW-SE and occur outside the margins of the Loch Doon granite erratics train, which reaches 610 m only on the SW face of the summit. This indicates that ice over-rode the southern end of the Kells range at a higher level than is shown by the erratics.

2) The Carsphairn Lane - Water of Deugh - River Ken valley

Glacial striae are for the most part only sporadically visible in this area, for extensive till deposits conceal the underlying bedrock. On the eastern flanks of the Kells range, however, the excavation of corries and troughs by ice has led to a greater exposure of bedrock. Till is also of limited extent to the south of Polharrow valley.

In general the striae in the corries by Lochs Dungeon and Harrow and the ice-scoured valley heads of the Polmaddy and Garryhorn valleys indicate ice movement toward the east and NE. SE of the Loch Dungeon corrie, however, abundant striae trend NW-SE, which suggests that the flow of basal ice was rapidly deflected into this direction after leaving the corrie (Figure 5.7). This sudden change in the direction of movement may possibly have been due to the effect of major ice streams nourished in the corries cut into Corserine farther north, as the striae from the latter show the same orientation.

This evidence suggests that in the southern section of the Carsphairn Lane - Water of Deugh - River Ken valley, the major ice streams crossed this valley at an oblique angle. Moreover, it seems that the ice flow here was little constrained by the underlying relief, the interaction between different ice streams being a more important controlling factor.

Farther north by Dundough Hill striae, while only few in number, tend to mirror the trends of the Cairnsmore of Carsphairn granite and Caradocian conglomerate erratics trains as well as being orientated at right-angles to the alignment of the cross-valley ridges (i.e. parallel to the valley axis). This contrasts markedly with the main trend of ice movement in the southern part of the valley, and its significance will be discussed further in Chapter 12 with reference to the origins of the cross-valley ridges.

At the northern end of the valley striae are exposed only on the eastern slopes of the Kells range, by Black Craig and Cullendoch Hill. These display a general SE-NW trend that is again confirmed by the distribution of granite and conglomerate erratics in this area.

5.8 ICE-MOULDED LANDFORMS

Despite the evidence presented so far demonstrating the intensity of glacial erosion in the Loch Doon basin and on the surrounding uplands, the development of ice-moulded landforms is of secondary importance within this area. On certain parts of the granite outcrop the bedrock has been strongly grained by ice that moved either north or south, parallel with the dominant trend of the joint system (McIntyre 1947; Ruddock 1969). This effect is well displayed

immediately south of Loch Macaterick, to the south and SW of Loch Doon and immediately east of Loch Girvan Eye (Figure 5.7). On Craignaw and Craiglee, the N-S graining is again in evidence, but here the ice has also etched out the other major joint maxima, at 80° and 120° (Ruddock 1969), imparting a "criss-cross" pattern on the major trend. This suggests that although the graining effect may be useful in indicating ice movement directions, it should be used with care and only then in combination with other evidence.

Within the whole field area, ice-moulded landforms are best developed in that part of the Carsphairn Lane - Water of Deugh - River Ken valley lying to the south of Dundough Hill (Figure 5.7). In this area, drumlins are the most characteristic landform and these are almost entirely confined to the eastern side of the valley. Here, they average 400 m in length and 20 m in height, although some occasionally attain 30 m, and form smooth, streamlined hills. They show the usual asymmetry of drumlins, being steeper on the side from which the ice came, in this area the NW-facing side.

The direction of ice movement recorded by the drumlins is in accord with that displayed by striae on adjacent bedrock exposures. The presence of the latter as well as the existence of well-defined rock drumlins, especially by Blawquhairn Farm (Figure 5.7), within the drumlin field itself serve to illustrate that even in this area of abundant glacial deposition, the ice also actively eroded the bedrock.

The western side of the valley at this point is characterised by numerous rocky knolls and ridges that are the product of ice roughening. Only on the valley floors of the Garroch, Glenlee and Polharrow Burns are drumlin forms encountered (Figure 5.7), but even these are not

"classic" drumlins in morphology and appear to a large extent bedrock controlled. Moreover, the upstanding bedrock knobs have favoured the development of crag-and-tail features. A good illustration of this form occurs by Polquhanity Farm where a smoothed and elongated drift tail occurs behind a large bedrock knoll that is approximately 15 m high (Figure 7.7). The tail is multi-crested and aligned NW-SE, which is the dominant direction of ice movement in this area. The importance of ice erosion can also be demonstrated in the above-mentioned area, and in particular on the eastern parts of the inter-fluves between the Polmaddy, Polharrow and Garroch valleys. The ground is largely till covered and forms a series of swells and depressions generally aligned NW-SE. Slopes are usually gentle and moderate but in many places small bedrock knobs protrude through the drift, indicating that the till has little depth. It appears that the till has done little more than smooth out the minor irregularities in the rock surface, and despite the veneer, the landscape here is essentially an erosional one.

At the northern end of the Carsphairn Lane - Water of Deugh - River Ken valley ice-moulded features are again very much in evidence. Moutonnée bedrock forms displaying a striking pattern of grooves and polished surfaces occur by the shores of Loch Doon and were described as early as 1865 by A. Geikie. Further, by the Eriff Burn, drumlin forms up to 500 m in length occur sporadically and are aligned SE-NW, mirroring the pattern of ice flow inferred above from glacial erratics and striae.

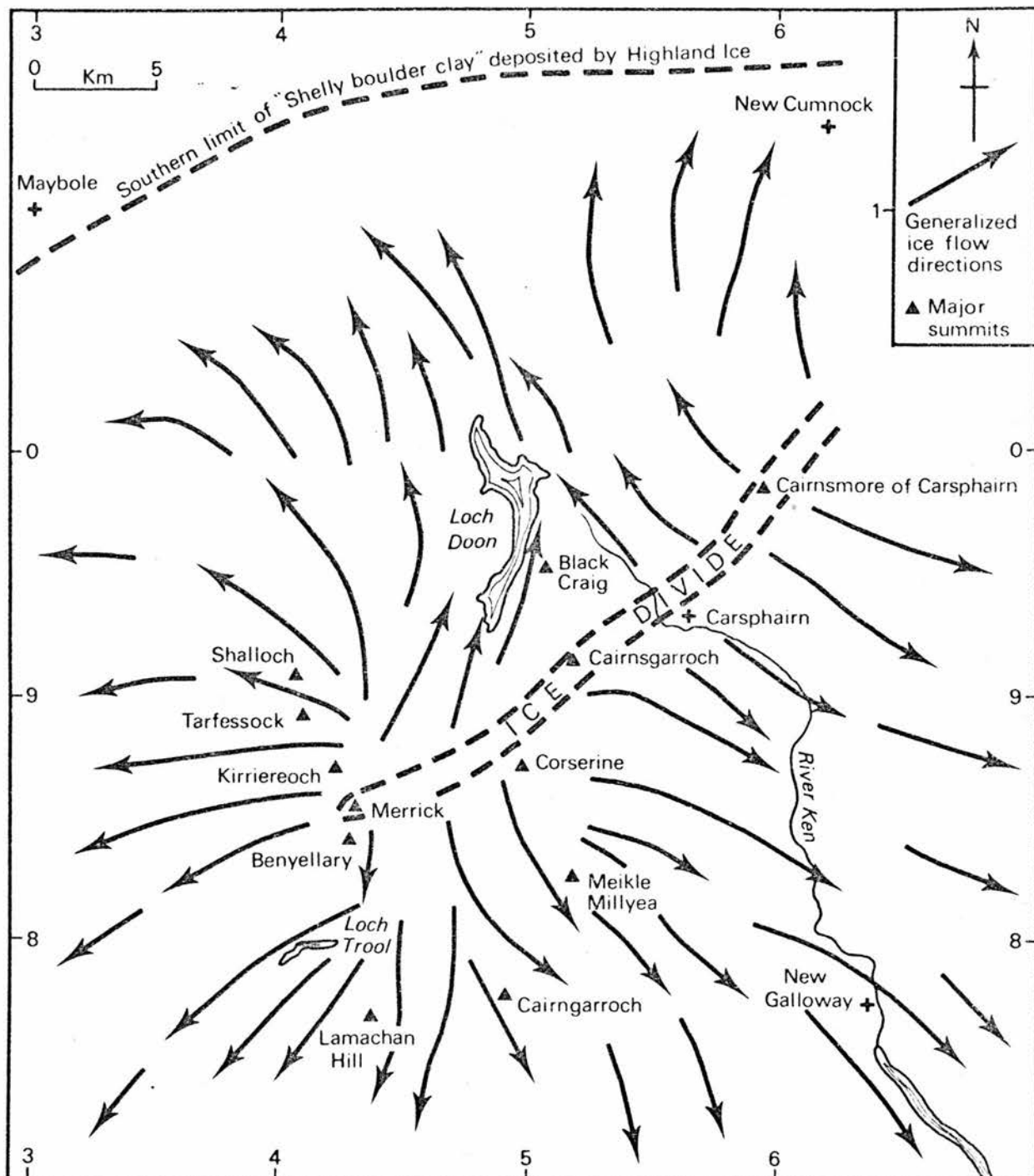
5.9 CONCLUSIONS

The conclusions regarding the possible directions of ice movement within the study area have been presented at the end of each section and are summarised in Figure 5.8.

Evidence abstracted from these conclusions provides information from which estimates relating to ice-sheet thicknesses can be made. Striae have been observed up to an altitude of 760 m on the Merrick range, while granite erratics have been found on or near various summits up to an altitude of 843 m. Such evidence shows that all of the field area was formerly covered by ice. Yet such evidence gives only minimal altitudes. In the western part of the British Isles, the Highland ice-sheet contributed directly to the southern extension of the Late-Devensian ice-sheet. Ice moved down the Firth of Clyde and into the north Irish Sea basin, where a lobe pushed into the low-land area between Wales and the Pennines to terminate along the Wolverhampton Line (Worsley 1970). This view is supported by evidence collected from the distribution of Ailsa Craig reibeckite-aurite erratics (Wright 1937, Figure 37). The distance the Scottish ice extended southwards implies that in its heart area, its surface stood far above the highest mountain summits, and a figure of 1500 m for its surface has been estimated by Sissons (1976). One might therefore hazard a guess that the surface of the ice-sheet that covered the western Southern Uplands stood some 1200 m above present sea level.

The great importance of this ice dome in the Southern Uplands context is attested by the radiating breaches and over-ridden cols, and by the almost radial distribution of granite erratics, as well as

Figure 5.8 Map of generalised ice flow directions and the position of the ice-divide during the Late-Devensian maximum in the W-C Southern Uplands. Southern limit of "shelly boulder clay" after Richey *et al.* (1930).



by the apparent absence of "foreign" erratics. This in turn suggests that the dome was sufficiently powerful to fend off the large ice streams flowing south from the SW Grampians.

CHAPTER SIX
THE LATE-DEVENSIAN ICE-SHEET DEPOSITS
OF THE LOCH DOON BASIN

6.1 INTRODUCTION

This chapter describes and discusses the glacial deposits located on the western flanks of the Rhinns of Kells range, in the Loch Doon basin itself (including the area to the west of Loch Doon and River Doon in the north) and on the eastern and western sides of the Merrick range. The limits of seven former glaciers that are considered to have developed during the Loch Lomond Stadial have also been mapped in this area (four others formed on the eastern side of the Rhinns of Kells). The deposits associated with these limits are described in Chapter 13.

As indicated in Chapter 5, this part of the study area was a major ice accumulation zone during the Late-Devensian and the landscape is consequently dominated by landforms of glacial erosion. Glacial deposits are therefore of only limited extent. However, it is possible that the extensive blanket peat accumulations in the Gala, Cooran, Eglin and Tunskeen Lanes conceal further deposits, but the extent of these is unknown and will not be speculated upon.

6.2 THE LATE-DEVENSIAN ICE-SHEET DEPOSITS

The glacial deposits in this area are considered under five sections, namely

- (1) the Lamechan Hills,

- (ii) the western Rhinns of Kells and the Gala Lane - Cooran Lane U-valley.
- (iii) the central Loch Doon basin and eastern Merrick range,
- (iv) the western part of the Merrick range,
- (v) the northern Loch Doon basin and Carrick areas.

(i) The Lamachan Hills

This area covers the range of hills between the Loch Trool and the River Dee glacial breaches as well as the U-shaped valley immediately to the north, which is occupied by the Glenhead Burn (Figure 5.1). In this latter area glacial deposits occur only sporadically, moutonnée bedrock landforms being impressively developed in most parts of the valley. The lower reaches of the Trostan Burn valley (NX 438794) are occupied by subdued and irregular hummocks of till 1 - 4 m high. Small sections in these revealed a very friable, sandy till containing sub-rounded boulders of granitic rock up to 50 cm in diameter. Similar boulders also cover the surface of the hummocks. Jolly (1867) considered these features to be "moraines". Many, however, are peat or till-blanketed bedrock knolls. Those that are composed of till are orientated E-W (parallel to the axis of Trostan Burn), while those by the Glenhead Burn - Trostan Burn confluence (NX 438794) are orientated SE-NW. These observations suggest that the hummocks are not moraines, but drumlinoid forms, for they parallel the direction of former ice movement in this part of the area.

Farther NW by the Glenhead Burn - Gairland Burn confluence (NX 426804) are two drift mounds 5 - 8 m high. A small quarry cut into one of these mounds showed 3 m of very coarse, unstratified sand

and gravel. The deposit comprised well-rounded granitic cobbles and boulders set in a loose sandy matrix. Charlesworth (1926a, p.11) stated that these were "block moraines" associated with the retreat of the "Cree Glacier". However, the internal composition of these landforms suggests that they form a small kame complex associated with final ice wastage in the area. A similar feature is located 600 m to the west by Buchan Farm (NX 419805).

Glacial deposits are only scantily represented within the Glen Trool breach. Small exposures of friable, sand-rich till, containing a mixture of granitic and greywacke clasts, occur in isolated hollows between bedrock knolls, again indicating that depositional agencies were of secondary importance in this area.

The Lamachan Hills to the south display a varied landscape of rolling summits cut by corrie-like forms and breaches. Till deposits are confined to the floors of these features of glacial erosion. The northern slopes of Cambrick Hill are plastered with an amorphous spread of till from which large boulders of granite protrude. The upper reaches of Sheil Burn are incised into these deposits. Sections up to 5 m in height showed a fairly compact grey-brown bouldery till with a sandy matrix. The drift thins upslope and terminates in a well-defined drift limit at ca. 550 m O.D.

The north-facing Nick of Curleywee corrie shows two well-developed rock steps that divide it into two sections. The more southerly of these steps was termed a "side moraine" by Moar (1989, p.446), but good exposures show this "ridge" to be composed entirely of *in situ* metamorphosed greywacke bedrock. Behind (south) this feature occasional peat-covered and randomly orientated till mounds

occur on the corrie floor. These are very subdued in morphology (2 - 4 m high) and some may be peat "barrels", for exposures in them are rare. The mounds and the floor of the corrie are strewn with sub-rounded granite boulders derived from outcrops farther north. It would seem therefore that the suggestion made by Moar (1969) that the Nick of Curleywee corrie nourished a glacier during the Loch Lomond Stadial is completely unfounded. No moraine is present in the corrie and the lochan from which Moar recovered his samples is well-drained and often dry, which may account for the absence of Lateglacial sediments. Moreover, if the corrie had been occupied by a glacier during the Loch Lomond Advance phase, then it might be expected that the granite erratics present would have been cleared from the rear of the corrie by the ice, as is the case with Loch Lomond Advance limits mapped elsewhere in the Loch Doon basin.

The floors of two N-S orientated valleys, occupied by Green Burn and White Laggan Burn, are masked by till deposits. In the former valley these deposits comprise a formless "blanket" that thins towards the east terminating in a drift limit at ca. 400 m O.D., below the summit of Cairn Garroch. The till is thicker and more massive in the lower sections of the White Laggan Burn valley (north of the over-ridden col at NX 466768) and forms a continuous spread into the lower reaches of Black Laggan Burn valley to the east. Here the present stream is incised into the till cover by up to 8 m in places. Morphologically the till is largely amorphous valley-fill, but several large, but ill-defined, hummocks up to 8 m high occur to the north of the rock step at NX 468770. Charlesworth (1926a, p.16) referred these hummocks to his "corrie moraine" series. However, the features do not

show the moraine-like form that characterises the Loch Lomond Advance corrie glaciers in the area, and it is more likely that their hummocky form has been exaggerated by the incision of the White Laggan Burn into the till. Numerous sections by Forestry Commission roads in this area showed a pale brown (10YR, 6/3), sand-rich till, which was fairly indurated and contained boulders of granitic and hypersthene rock up to 2 m in diameter.

Although the River Dee breach shows signs of scouring by ice and bedrock is exposed in places, glacial deposits are present in the form of large, isolated till mounds up to 5 m high. The best developed is a ridge-like feature (NX 498794) that extends part of the way across the floor of the breach and is orientated NE-SW (perpendicular to the direction of former ice movement). A large section cut into the ridge showed a pale brown (10YR, 6/3), sandy till with a fairly high silt and clay content (particle-size analysis of the till shows it to be composed of 59.5 per cent sand; 27.0 per cent silt; 13.5 per cent clay). This is probably due to the deposit being located on metamorphosed greywacke bedrock, which would provide a source for silt- and clay-size particles. This suggestion is supported by the presence of metamorphosed greywacke clasts in the till section. Sub-rounded granite boulders up to 2 m in diameter were also well represented, as were cobbles of hypersthene rock. The till was quite friable and possessed a blocky structure. This feature was referred to by Charlesworth (1926a, p.13) as a retreat moraine associated with the "Ken Glacier" and is probably the closest to a moraine of all the landforms described by Charlesworth in his paper. The ridge, however, appears to be located in an anomalous position, occupying the

central part of the River Dee glacial breach where ice erosion would have been most intensive. It is possible that the ridge was formed during a still-stand phase as the ice-sheet retreated, but from what is known of the form of ice-sheet wastage in the area this seems unlikely. Thus, in the absence of equivalent landforms in the Loch Doon basin the exact mode of formation of this ridge and its place in the chronology of the area remain equivocal.

(11) The western Rhinns of Kells and the Gala Lane - Cooran Lane valley.

The floor of the Gala Lane - Cooran Lane valley is almost completely masked by thick peat accumulations, including the raised bog of the Silver Flowe in the Cooran Lane part of the valley. As a result, glacial deposits are only rarely exposed. However, on the eastern side of the valley (western slopes of the Rhinns of Kells) till deposits are locally extensive. In the valley of Cleugh Burn the till displays valley-fill morphology with occasional hummocks that possess a random orientation. A similar pattern is exhibited in the valley of Downies Burn NE of the Backhill of Bush bothy. Here the stream shows up to 6 m of incision into the till, which is fairly compact and sand-rich. A small quarry cut into these deposits (NX 491851) revealed a yellowish-brown (10YR, 5/4), sand-rich till (particle size analysis results show 80.8 per cent sand, 14.6 per cent silt, 4.6 per cent clay), with a high gravel and boulder component of granitic rock.

Till also covers the lower south-facing slopes of Meikle Craigtarson farther to the north, but the deposits are generally more

attenuated than those to the south and bedrock knobs commonly protrude through the drift cover. In places this arrangement produces elongated ridges that can be mistaken for drumlinoid landforms (e.g. the ridges developed at NX 484850). Similar forms also occur in the col between Cleugh Burn and Downies Burn (NX 495840) and on the summit of the Tops of Craigeazle (NX 492834), although the latter are not till covered. These bedrock-controlled ridges provide useful evidence of the direction of former ice movement in the area, striae being of restricted occurrence on the granitic rocks.

North of Meikle Craigtarson a well-defined drift limit follows the approximate granite/metamorphosed greywacke contact for 2.2 km at an altitude of ca. 350 m. Above this limit the steep rocky slopes of the Kells range rise to over 600 m, while to the west till deposits are extensively developed in places. The till generally takes the form of "ridges" that are orientated S-N. The majority of these ridges, however, are again bedrock controlled, the till being only 1 - 3 m thick. North of Loch Head Burn the till fades out, giving way to extensive areas of ice-moulded bedrock. In this same area, towards the axis of the Gala Lane valley, the till deposits thicken to 4 - 5 m but bedrock knolls are still much in evidence. One esker also occurs in this area (NX 467893), orientated perpendicular to the valley axis, 250 m long and 3 - 5 m in height.

As the western slopes of the Cooran Lane - Gala Lane valley are very much steeper than those of the east, glacial deposits are of limited extent. Small amorphous till mounds occur between Round Loch of the Dungeon (NX 466845) and Long Loch of the Dungeon (NX 478842) and below The Slock (NX 460896). The complete absence of any

moraine-like form to the former deposits indicates that Charlesworth's reference to them as being "corrie moraines" deposited by "ice from the depression south of Dungeon Hill" (1926a, p.16) is erroneous.

Irregular till hummocks occur to the south of Snibe Hill, by the confluence of the Cornarroch Strand and Cooran Lane streams (NX 469812). Sections in the stream banks here showed a fairly friable, pale brown till, containing granite boulders up to 1.5 m in diameter. The hummocky morphology of these deposits is largely due to incision by the present stream, which has exaggerated their form. There is no evidence to suggest that these deposits are retreat moraines (cf. Charlesworth 1926a).

The extensive spreads of granite boulders that mantle most of the slopes on the western side of the Cooran Lane - Gala Lane valley and the large moraine located by The Tauchers (NX 4687) will be described and discussed in the chapter dealing with the Loch Lomond Advance glacier limits.

(iii) The central Loch Doon basin and the eastern Merrick range.

The part of this area of dissected upland south of Loch Enoch is characterised by widespread exposures of ice-moulded bedrock (e.g. the summit of Craignaw) and rock basin lakes (e.g. Loch Arron and the Glenhead Lochs), some of which are also drift dammed (e.g. Loch Valley) (Figure 5.1). Certain areas, in particular hollows between bedrock ridges, are blanketed with thin deposits of till, which is generally sand-rich and friable. For example, in the area immediately north of Loch Neldricken (NX 450835) the till has a rather featureless morphology and is thinly draped over the bedrock, through which moutonnée bedrock knolls commonly protrude. Occasionally the

till takes the form of hummocks or elongated ridges, as seen to the NW of Loch Neldricken on the lower slopes of the Rig of Loch Enoch (NX437832), although some of these are again bedrock cored. The drift also takes the form of conical mounds at the western end of Loch Valley (NX 438818). These features, which effectively dam the lake, are up to 12 m high and are separated by kettle holes. Jolly (1867), Charlesworth (1926a) and Eckford (1955) described these latter deposits, suggesting that they were moraines; Charlesworth indicated that they were deposited during the retreat of the "Cree Glacier". However, the morphology and location of these features suggest that they were deposited supraglacially during ice-sheet stagnation.

Both Jolly (1867) and Charlesworth (1926a) made reference to a series of moraines in the valley occupied by Buchan Burn. Jolly mentioned a "moraine" extending completely across the valley where the Buchan Burn forms a hanging valley to the north of Loch Trool (NX 416811) and stated that a lake was formerly impounded behind it. Although small mounds of till are present in this part of the valley, the ridge referred to by Jolly is bedrock with a cover of silt-rich till 1 - 2 m thick. In addition, no evidence was found to confirm the former presence of a lake in this area. The "valley moraine" sequence located farther to the north by Culsharg Farm (NX 415822) and again in the area to the NE of this steading was considered by Charlesworth (1926a, p.16) to form part of the "Minnoch Series" of moraines associated with the retreat of the "Cree Glacier". Inspection of these ridges referred to by Charlesworth (and Jolly) showed all to be bedrock cored with only a thin cover of either peat or till.

Although visible glacial deposits are of limited extent on the floor of the Buchan Burn valley, the extensive postglacial deposits (peat and fluvial) that mantle the floor may conceal further accumulations of till. Massive till deposits with a valley-fill morphology are present, however, in the embayment between Bennan and Benyellary summits. These have been cut into by the Whitehand Burn and its tributaries. Sections up to 8 m high showed a greyish boulder-rich till with a silty matrix (cf. Jolly 1867) within which greywacke clasts were dominant.

In the upper reaches of the Buchan Burn a large area of till with a series of elongated ridges on its surface (orientated NE-SW and paralleling the valley axis) occurs on the NW side of the valley (NX 431841). These ridges reach a maximum height of 10 m and form part of a complex that extends for 500 m downvalley from the confluence of Gloon Burn with Buchan Burn. Sections in the stream banks showed a fairly indurated till, greyish-brown in colour and containing granite and greywacke cobbles and boulders. No bedrock outcrops were found within this till mass although, given the amount of bedrock control already discussed in this valley, it is possible that there may be a core of bedrock. The features appear to be drumlinoids or large flutes (the largest being 120 m in length), this suggestion being supported by their orientation, which is parallel to the direction of former ice flow in the valley.

The Late-Devensian ice-sheet deposits in the area to the north of Loch Enoch are complicated by the occurrence, in parts of some valleys, of deposits laid down by Loch Lomond Advance glaciers. Other complications arise through the masking effect of extensive

blanket peat deposits in the valleys of Eglin Lane and Tunskeen Lane. The ice-sheet deposits are characterised by subdued till hummocks, 1 - 4 m high, which in places are aligned parallel to the valley axes, while elsewhere they possess a more random orientation. Exposures in these mounds are very limited, but where they do occur show a friable, sand-rich till with occasional clasts of granite. The lack of exposures and subdued nature of these landforms means that some may be composed entirely of peat, although the writer was careful not to include doubtful forms in the mapping. Hummocks are present in the lower reaches of the Caldron and Saugh Burn valleys as well as by their confluence with the Eglin Lane (NX 441876). Farther to the NW, the summits of Rig of Millmore, Macaterick Hill and Castle-on-Oyne are clear of debris, and show evidence of extensive ice-moulding. Between these ice sculptured ridges till mounds, heavily masked by peat, occur on the floors of valleys occupied by Tunskeen Lane and Castle-on-Oyne Burn. These deposits are confined within well-defined drift limits between 350 and 400 m O.D. on both sides of the Tunskeen Lane valley as well as in the valley occupied by the unnamed stream immediately to the west. Above these drift limits the hill slopes of the Merrick range exhibit steep rocky slopes that are littered with granite boulders.

Certain of the till hummocks described above (those in the Caldron Burn and Eglin Lane valleys) were considered by Charlesworth (1926a, p.16) to be related to his "Corrie Moraine" stage, which he regarded as representing the final phase of ice-sheet retreat in the area. Observations by the present writer indicate that these deposits bear no relation to 'retreat moraines'. Also it is difficult to

envisage, especially in the light of what is known of the form of ice-sheet decay in Scotland (Sissons 1967a), an orderly retreat of ice along these valleys so close to the ice accumulation zone and leaving behind a series of retreat moraines. The location of the ridges, being confined to valley floors, suggests deposition from ice that was greatly controlled by the surrounding relief. Thus it seems likely that they were deposited during the later stages of ice-sheet retreat. The general orientation of the ridges parallel to the valley axes suggests that the ice was active during this phase, producing drumlinoid landforms. However, the presence of more randomly orientated hummocks also implies that deposition occurred at some stage after ice movement ceased.

(iv) The western part of the Merrick range.

The ice-sheet deposits on this side of the Merrick range are confined to the four E-W orientated valleys lying between the western extensions of the summits of Benyellary, Merrick, Kirriereoch, Tarfessock and Shalloch-on-Minnoch. As the western boundary of the study area excludes the lower sections of these valleys and as the upper parts of two of them contain deposits considered to have been laid down by Loch Lomond Advance glaciers, the Late-Devensian ice-sheet deposits described here are of limited extent.

The southernmost valley, between Benyellary and Merrick, is occupied by the Kirkennan Burn and its tributaries. The part of the valley mapped has only thin deposits of till that blanket the sides and floor of the trough. These deposits have been cut into by the Kirkennan Burn to a depth of 2 - 3 m. Jolly (1867, p.173) drew attention to the westward continuation of these deposits in his account

of the area, stating that the more westerly sections of the valley (especially the area by NX 395845) have " . . . been filled to a depth of from 30 to 60 and 100 feet with the glacier clay. The present considerable stream flows between perpendicular walls of boulder clay, fifty feet and upwards, along which their interior composition is beautifully displayed". Riverbank sections examined by the present writer showed a fairly indurated, greyish-brown till with a silty matrix. Greywacke boulders and cobbles were present in abundance, but clasts of granite were significantly absent (see Chapter 5 for discussion of this phenomenon). The "corrie moraines" stated by Charlesworth (1926a) to be present in this valley were not located, despite detailed mapping of the area.

The eastern sections of the large glacial trough that lies between Merrick and Kirriereoch summits are occupied by deposits of a Loch Lomond Advance glacier (Figure 13.2A and Chapter 13). To the west of this glacier limit (i.e. west of National Grid easting 41) massive till deposits blanket the southern side of the valley below an ill-defined drift limit at ca. 450 m. On the northern side of the valley floor are large, irregular mounds of till, some bedrock controlled and 4 - 5 m in height. These terminate at NX 402863 and are replaced by thick deposits of till possessing a valley-fill morphology. The Kirshinnoch Burn, which occupies the trough, is deeply entrenched into these deposits, with steep bluffs up to 8 m high on each side. Sections revealed a light brown till with a sandy/silty matrix that was fairly friable. Boulders of both granite and greywacke were present.

A similar pattern of landforms is located in the glacial trough between the summits of Kirriereoch and Tarfessock. To the north and

NE of the clearly defined Loch Lomond Advance moraine there are large, sub-parallel till ridges 4 - 6 m high and up to 120 m long present (Plate XIV). The ridges are generally orientated E-W and extend from just below the Carmaddie Brae col to a point 800 m west where they merge into thick valley-fill deposits into which the Cross Burn is incised. Exposures in both sets of landforms (ridges and valley-fill) showed a pale brown (10YR, 6/3) silty till, which was quite compact; both granite and greywacke clasts were present in the till. A similar, although less well-developed, sequence of ice-sheet landforms occurs in the trough lying between Tarfessock and Shalloch-on-Minnoch summits. The eastern section of the valley contains isolated till hummocks 2 - 4 m high that give way to thick valley-fill deposits farther west.

It is possible that the similar pattern of ice-sheet landform development in both the Kirshinnoch and Cross Burn troughs may be due to the influence of relief over former ice flow and the conditions of till deposition. The confined and streaming effects on ice flowing through the cols in the Merrick range may have encouraged deposition of elongated drumlinoid ridges, whereas farther to the west, where the troughs become more "open", then deposition of till with a valley-fill morphology became the norm.

(v) The northern Loch Doon basin and Carrick areas.

The landforms of the northern part of the Loch Doon basin (west of Loch Doon and north of Loch Macaterick) and the Carrick area are dominated by ridges of ice-moulded bedrock (e.g. the summits of Craigmawhannal (NX 4691), Craighionn (NX 446917) and Craigmashennie (NX 415928)). Smith (1898, p.82) drew attention to this fact stating

that " . . . the area has very little boulder clay, and this is simply because the glaciers began earlier and continued late in the district, not forming 'ground moraine' . . . its surroundings are highly *moutonnées*". The inter-ridge hollows are masked by extensive accumulations of blanket peat, and thus estimates of the probable extent of till are impossible to make. In an attempt to overcome this difficulty, borehole data for the Loch Riecaur dam (NX 441936) were inspected. These data showed peat deposits (1 - 4 m thick) resting directly on hard granite bedrock. Trial excavations made in 1969 for the new Loch Bradan dam farther north (NX 433981) revealed deposits of till in the valley occupied by the Water of Girvan (Johnston 1974). On the western side of this valley depth to rock-head was found to reach a maximum of 9 m. Below a cover of peat (depth unspecified) till with a silt-rich matrix and numerous boulders was described. Johnston indicated that although there was little difference in the colour or particle-size characteristics of the till with depth, the lower layers were much more compacted (with an *in situ* density of 2400 kg/m^3) than the upper layers. This difference was interpreted as being due to the till being deposited by two different glaciations. The uniform nature of the till, however, in terms of both particle-size and colour suggests that the whole unit was deposited during the same glacial period, the differences in compaction probably being due to varying amounts of porewater present during lodgement of the till (cf. Boulton and Paul 1976).

Small pockets of till are exposed at the side of a Forestry Commission road just to the west of the shores of Loch Doon (NX 472943; NX 477943; NX 481944). These deposits comprise small

hummocks that are either banked against the up-ice flanks of bedrock ridges or in the hollows between. At the last mentioned location above, a section 3 m high showed a fairly compact, pale brown (10YR, 6/3), sand-rich till (particle-size analysis: 78.3 per cent sand, 16.9 per cent silt and 4.8 per cent clay), with clasts of granite well represented.

North of the range of low hills of metamorphosed greywacke that fringe the northern margin of the Loch Doon granitic intrusion deposits of till are more in evidence. The bedrock depression within which Loch Finlas and Derclach Loch are situated is floored by a blanket of till that is punctuated by numerous, irregular till hummocks. The protrusion of numerous bedrock knolls through this cover suggests not only that the till is thin, but that some of the hummocks may have bedrock cores. Sections in these deposits are very limited; small exposures showed a compact olive till with a silty matrix containing cobbles of greywacke and granite. The valley between Wee Hill of Glenmount (NX 021451) and Maratz Hill (NX 023433) shows further evidence of till deposition as does the valley entrenched along the line of the Southern Uplands Fault and occupied by Glessel Burn. Well-developed rock-cored drumlins and crag-and-tail features up to 10 m high and 300 m long are located in the former valley, while in the latter the till takes the form of thin valley-fill. The upper reaches of the SW-NE orientated valley of the Shalloch Burn immediately to the north is occupied by massive hummocks of till that have been partly dissected by fluvial action. These features reach 15 m in height and 700 m in length (e.g. NX 440030, NX 448037) and possess a drumlinoid morphology, although this may have been exaggerated

by the fluvial incision that has taken place on both flanks of the deposit.

This apparent increase in till deposition towards the north of this part of the Loch Doon basin may be partly explained by the reduced cover of blanket peat, but the sheer bulk of the deposits indicates a change in the depositional characteristics of the ice at this point. Noticeably the till is confined to the river valleys and depressions. Nobles and Weertman (1971) have suggested two factors that may promote deposition of till, from active ice, in depressions rather than on upstanding areas:

- 1) the geothermal heat flux tends to be focused on hollows in the glacier bed, therefore melting more ice and increasing deposition, and
- 2) temperature gradients at the base of an ice-sheet tend to be lower over depressions, which increases the amount of ice melted and hence promotes deposition.

Although these factors are important, it is probable that the bedrock geology and structure have also played a fundamental part in this sequence of deposition. The major S-N joint pattern of the granite has influenced the creation of S-N orientated valleys in the northern part of the pluton (e.g. Tunskeen Lane and Eglin Lane valleys), which parallel^{the} direction of former ice movement. This, together with the relatively impermeable nature of the granite, would have tended to decrease effective normal pressures, limit the deposition of till to forms of least resistance (low drumlinoids in this case) and promote erosion (cf. Boulton 1974). It is noticeable that the granite bedrock ridges show more signs of ice-moulding and streamlining than do the unmetamorphosed greywackes, Old Red Sandstone and Carboniferous

rocks to the north, which may indicate more intense abrasion in the former area. To the north of the granite outcrop the river valleys are generally orientated NE-SW, perpendicular or oblique to former ice flow. In this area deposition would have been enhanced by increased effective pressure caused by the bedrock "roughness" as well as the permeability of the Old Red Sandstone and Carboniferous rocks, till being most abundant where these rocks crop out.

6.3 SUMMARY AND CONCLUSIONS

The part of the study area considered in this chapter is dominated by landforms of glacial erosion and these have been fully described in Chapter 5. Drift deposits associated with the Late-Devensian ice-sheet are of only limited extent, although locally they may attain considerable thicknesses. Deposits of sand and gravel are poorly developed, being confined to one small esker by Loch Doon and a kame complex by Loch Trool. Till deposits are invariably confined to the floors or lower slopes of glacial troughs or bedrock depressions. However, the masking effect of blanket peat deposits (especially on the granite outcrop) may conceal further accumulations, the extent of which is unknown.

The morphology of the till is variable, ranging from massive valley-fill to thin drapes overlying bedrock. Till hummocks, some with a drumlinoidal form are also well represented. Many of these latter deposits have been interpreted by certain workers as moraines associated with the retreat of the last ice-sheet to cover the area. Inspection of these hummocks has shown that:

- 1) some are bedrock cored with a thin mantle of till or peat;

- 2) some are orientated parallel to the direction of former ice-movement and therefore, by implication, associated with active ice; and
- 3) those possessing a more random orientation bear no resemblance to moraines *sensu stricto*; they are interpreted as being associated with ice-sheet downwastage rather than an orderly retreat along glacial troughs.

In the valleys and depressions to the west and north of the granite pluton, till deposits increase in extent. These deposits usually possess a valley-fill or drumlin morphology. It is suggested that this pattern is a function of the structure and lithology of the bedrock which controlled ice velocity, erosion and the conditions of till deposition from the ice-sheet.

The lack of sand and gravel deposits and associated ice wastage landforms (e.g. meltwater channels) is interpreted as being due to the rapid deglaciation of the area and the confinement of meltwaters to glacial troughs occupied by the present drainage system.

CHAPTER SEVEN
LATE-DEVENSIAN ICE-SHEET DEPOSITS
OF THE CARSPHAIRN LANE - WATER OF DEUGH -
RIVER KEN VALLEY

7.1 INTRODUCTION

This chapter presents the field observations made on the Late-Devensian ice-sheet deposits located in the Carsphairn Lane - Water of Deugh - River Ken valley and in the valleys on the eastern flanks of the Rhinns of Kells hill range (the valleys occupied by the Garryhorn, Polmaddy, Polharrow and Gerroch Burns). Attention will be focused on the cross-valley ridges mentioned in Chapters 3 and 4, which are best developed in the Water of Deugh section of the valley. As landforms of this type have not been reported from anywhere in Great Britain previously, detailed sedimentological analyses were carried out on the deposits (viz: particle-size analysis; analysis of geo-technical properties; roundness analysis and till fabric analysis) and these results are presented in the following four chapters. A discussion of the possible origins of these landforms is contained in Chapter 12.

7.2 THE GLACIAL DEPOSITS OF THE CARSPHAIRN LANE - WATER OF DEUGH -
RIVER KEN VALLEY

Owing to the extent of the glacial deposits the Carsphairn Lane - Water of Deugh - River Ken valley is divided into eight areas for the purpose of description (Figure 7.1A).

Figure 7.1

- A. Sub-divisions of the Carsphairn Lane -
Water of Deugh - River Ken valley
(see text).
- B. Glacial landforms in the area north of
the Carsphairn Lane watershed (section (1),
Chapter 7).

(1) The area north of the Carsphairn Lane - Muck Water watershed.

The area north of the watershed (300 m in altitude) is characterised by thick till deposits that occasionally display drumlin morphology. The latter occur on the northern and western slopes of Little Eriff Hill (Figure 7.1B), are 300 - 400 m long and up to 10 m high; they are invariably orientated SE-NW. These features are most numerous in the small valley occupied by Eriff Burn. One particularly good example occurs at NX 496013 and is covered by boulders of granite up to 1 m in length. A section cut by Eriff Burn in an adjacent swell (NX 495013) showed an indurated olive-grey, clay-rich till (5Y, 5/2) containing a few cobbles of metamorphosed greywacke and granite. Five hundred metres south of this section the eastern flanks of a drumlinoid showed 5 m of till resting on bedrock (NX 007496). The till here is clay-rich, grey to dark-grey in colour (5Y, 4.5/1), very compact and stony and contains boulders of metamorphosed greywacke up to 1 m in length.

The best developed drumlin in this area is on the eastern shores of Loch Doon (NX 498998). This "text-book" feature is 500 m long and 20 m high. Long sections in its western and SE flanks showed a uniform clay-rich, olive till (5Y, 5/3). The deposit was very indurated and difficult to excavate. Although greywacke and granite boulders (some reaching 2 m in length) were well represented, cobble and gravel-size clasts were less abundant.

This area also provides an interesting example of the close juxtaposition of landforms of glacial erosion and deposition. While the area by Little Eriff Hill shows extensive deposits of till, presumably from ice flowing north from the Carsphairn Lane valley (this

suggestion being supported by the general trend of the drumlins), Muckle Eriff Hill, immediately to the west, displays ice-moulded bedrock forms that are heavily striated and has little or no till (Figure 7.1B). The latter area lies due north of the Loch Doon breach (see Chapter 5, Section 5.3) and it is possible that increased ice velocity caused by the ice being forced through the narrow breach inhibited the deposition of till in this area compared with that farther east.

The hill of Bryan's Heights is also relatively drift free, but north of National Grid northing NX 030, a featureless till blanket is "draped" over the bedrock. The sharp increase in gradient as the Central Lowlands are approached, along with the change in lithology, may have influenced the pattern of deposition here.

Several large meltwater channels occur in this area (Figure 7.1B). The most impressive is occupied by Muck Water and the A713 road. From its intake ca. 295 m O.D. by Glenmuck Farm it extends for 5.2 km to the NW (1, Figure 7.1B). Two short, left-bank tributary channels join the main one in its upper reaches. These are ca. 15 m deep and cut in both till and bedrock. The floor of the more southerly of the channels (Plate II) is accordant with that of the main channel, while the other "hangs" by 20 m. The main channel is up to 40 m deep in places (especially SE of Mossdale Farm) and cut mainly into bedrock. At certain points, however, the eastern walls of the channel are entrenched into massive olive-grey till, which covers the lower flanks of Glenmuck Craig. By Mossdale Farm the channel is joined from the east by two channels. Here the floor widens and a small sand and gravel terrace complex occurs where the

channels become confluent. NW of this point the main channel becomes much attenuated, being cut mainly in till. Large (up to 1 m), rounded boulders of granite are strewn on the channel floor in this latter part.

This meltwater channel is much larger than any other in the study area. There appear to be two reasons for this.

- 1) The present writer and officers of the Geological Survey have measured striae located on the walls of the main channel (Figure 7.1B). These trend parallel with the channel itself (SE-NW). This evidence shows that the feature was in existence prior to deglaciation, but how much of it was produced by glacial erosion is unknown.
- 2) For a distance of 1.3 km between NX 502029 and where the Southern Uplands Fault crosses the channel (NX 494039) the latter follows the line of a barytes/lead vein, which was probably intruded at the same time as the granitic plutons farther south. This zone of weakness in the bedrock would explain its susceptibility to erosion by meltwaters, as well as by over-riding ice.

This evidence suggests that the meltwater channel is in part structurally controlled and was excavated to an unknown depth prior to deglaciation. The presence of the tributary channel, whose outlet is discordant with the main channel suggests that incision by meltwaters has been at least 20 m.

A second large meltwater channel west of Bryan's Heights (2, Figure 7.1B), is occupied by Gaw Glen Burn. It is cut entirely in bedrock and is 20 m deep in places. The intake is at ca. 260 m O.D.

and it trends WNW for 1.8 km to where it joins the third major melt-water channel (3, Figure 7.1B) in the area. This northward-trending feature is occupied by the waters of the River Doon and comprises a 25 m deep "gash" in bedrock. It is difficult to discern whether channel 3 has a continuation to the south, owing to the masking effect of Loch Doon and the dam at its northern end. However, observations by Murray and Pullar (1910) suggest that there may be a southerly extension below the waters of Loch Doon, for their soundings revealed a channel-like feature at least 500 m long and 6 - 8 m deep.

Striae in the vicinity of channel 2 trend S-N (Figures 5.7, 7.1B) which direction is oblique to the alignment of the channel, thus suggesting that it was not cut by ice. Channel 3, however, parallels the trend of former ice flow in the area, and although no striae could be found within it (due mainly to its inaccessible precipitous walls) it is possible that the valley was at least partly excavated by ice prior to meltwater incision.

As the meltwater channels appear to be intimately related to a series of depositional fluvioglacial landforms located in the NW part of the Carsphairn Lane valley, discussion of their position in the deglacial sequence is considered in section (ii) below.

(ii) The Carsphairn Lane valley.

The detailed morphology of the glacial landforms mapped in this area is shown in Figures 7.2 and 7.3. Both till and sand and gravel occur in this area: they will be considered separately.

The till landforms in the Carsphairn Lane valley are an extension of the area of cross-valley ridges located to the SE (see section (iv)).

Figure 7.2 Glacial landforms in the SE section of the
Carsphairn Lane valley (section (ii),
Chapter 7) and the Garryhorn valley (section
(vii, Chapter 7). Key as for Figure 7.3.

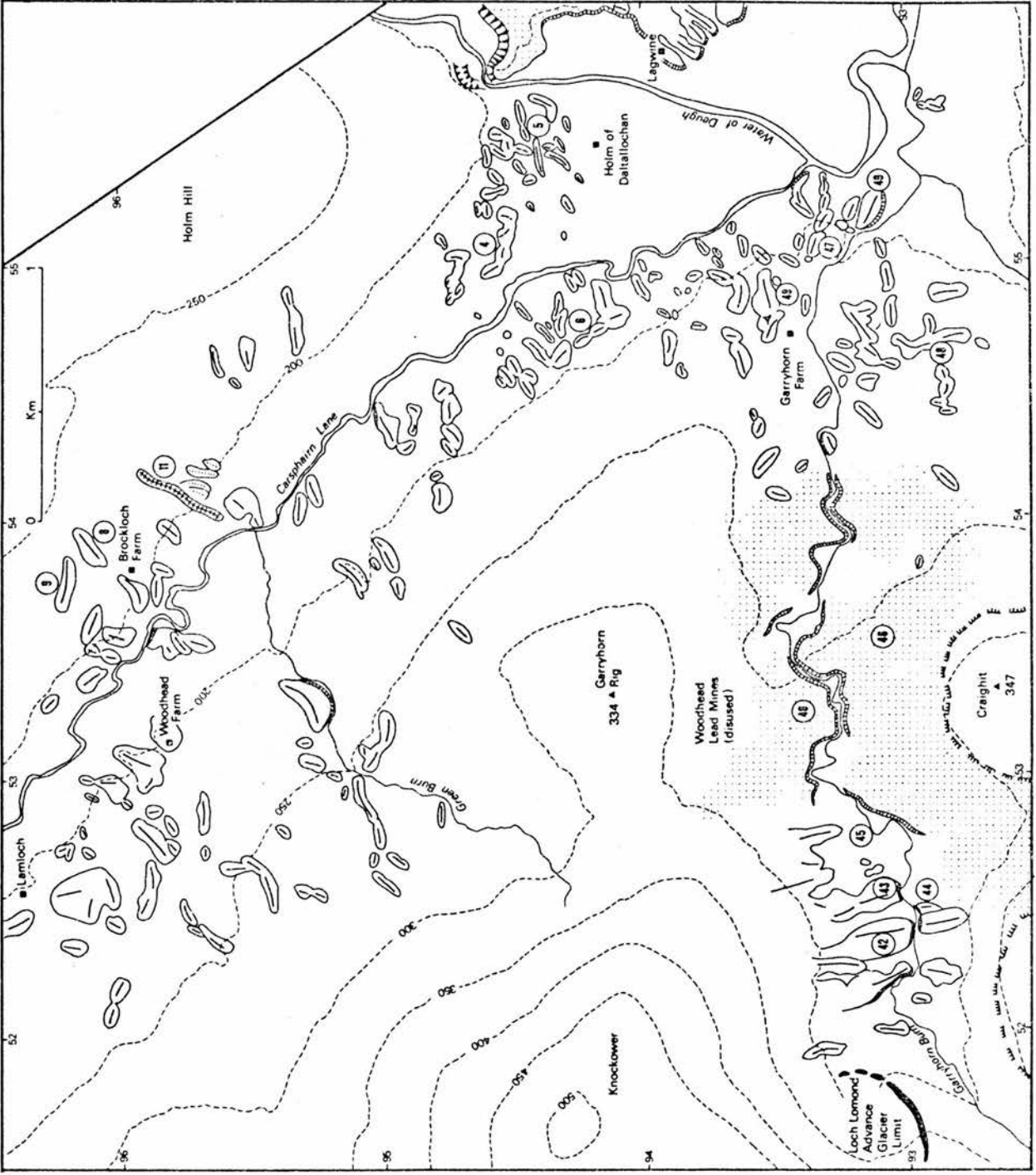
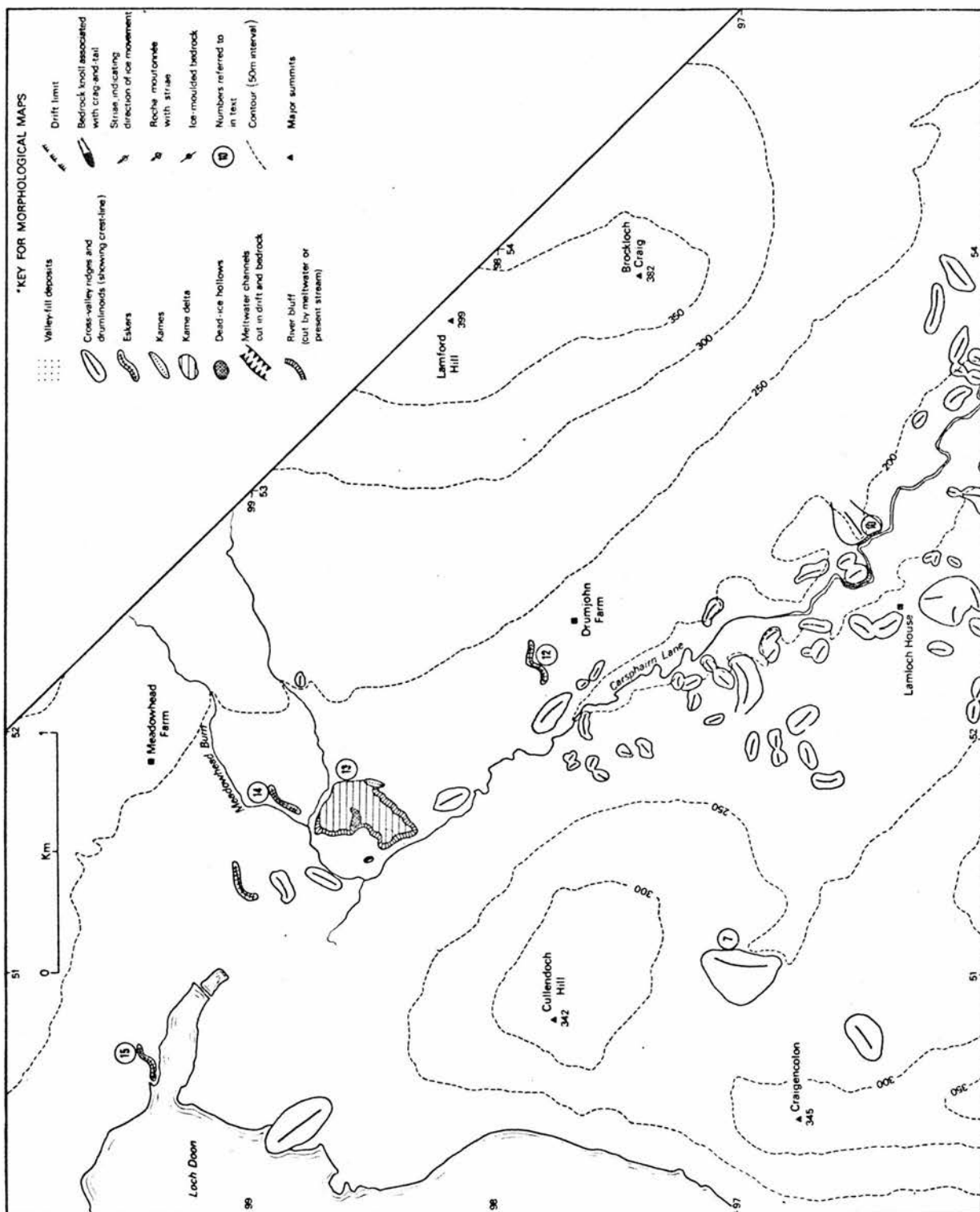


Figure 7.3 Glacial landforms in the NW section of the
Carsphairn Lane valley (section (11),
Chapter 7).



In the former area, the ridges only occasionally display a cross-valley trend. They vary from random clusters of elongate hummocks to drumlinoidal forms that are aligned parallel to the valley axis and the direction of former ice movement. In this respect they tend to resemble the "hummocky moraine" topography described from Canada and Scandinavia by numerous workers (e.g. Hoppe 1952; Stalker 1960; Henderson 1972) or the "till ridges" mapped by Cullingford and Gregory (1978) from Wensleydale, England. Some of the ridges are "beaded" (e.g. 4, Figure 7.2), elliptical or oval-shaped hummocks (up to 8 m high) being connected by low swells 3 - 4 m high. The ridges are usually less than 300 m long. They are confined to the valley-side slopes below 300 m O.D., most occurring below 250 m. Above these altitudes the ridges merge into a formless till blanket of variable thickness, which eventually gives way to extensive outcrops of bedrock. This pattern is particularly well shown on the eastern slopes of the Carsphairn Lane valley below the summits of Brockloch Craig and Lamford Hill.

The best ridges occur at the SE end of the Carsphairn Lane valley, probably because the valley is widest here. North of the Holm of Daltallochan the ridges are particularly well defined (5, Figure 7.2), being 5 - 8 m high with a fairly random orientation. On first appearance these forms resemble kame and kettle topography, but various sections (e.g. NX 554943) showed a silt-rich, olive brown till (2.5Y, 4/4). The till was indurated, very stony and contained a high percentage of cobble-size greywacke clasts.

On the western side of the valley (6, Figure 7.2) the ridges show a complex pattern. One large beaded till ridge, with an overall

length of 350 m and 3 - 5 m high, trends SE-NW, parallel to the direction of former ice movement. Connected to the eastern flanks of this ridge, by low swells, are several smaller ridges that are orientated SW-NE. This close association between landforms both parallel and perpendicular to the direction of ice movement is a common feature of many of the ridges in the Carsphairn Lane - Water of Deugh - River Ken valley, and suggests a genetic link between the two. Such a relationship is considered in more detail in Chapter 12.

Farther NW the ridges become more massive and elliptical and many are drumlinoid. North of Lamloch (Figure 7.3) any cross-valley trend to the ridges has largely ceased. Moreover, the ridges are generally confined to the valley floor and tend to be smaller than those to the SE (3 - 5 m high and less than 200 m long). An exception to this pattern is a large, isolated drumlinoid (7, Figure 7.3) that exceeds 300 m in length and is 8 m high. A small section excavated in the side of this feature revealed indurated, sand-rich till.

Exposures in the ridges of the Carsphairn Lane valley are quite common, especially in those cut by the A713 road. All those inspected showed sand/silt-rich, olive till containing numerous boulders of greywacke. For example, sections in the two ridges north of Brockloch Farm (8 and 9, Figure 7.2) showed indurated sandy till with a distinct blocky structure. The till contained abundant cobble- and gravel-size clasts of greywacke that were invariably surrounded by a thin lattice of coarse sand-size particles displaying an openwork structure. This phenomenon was also observed in all other sections in the area where the olive till was exposed. Dreimanis (1976, p.37) has argued

that such lattice structures probably represent "thawed-out ice layers poor in debris". In addition, the cobble- and gravel-size clasts were invariably coated with a thin layer of silt and clay particles. Again this was found to be a ubiquitous characteristic of the clasts examined from the olive till. It has been suggested (Elson 1961) that this feature is caused by the growth of ice crystals, which tend to expel particles of this size and promote their accumulation on the surface of pebbles and larger clasts. According to these authors, the two phenomena mentioned above are characteristic of debris that has been transported by ice in an englacial position and deposited as basal melt-out till.

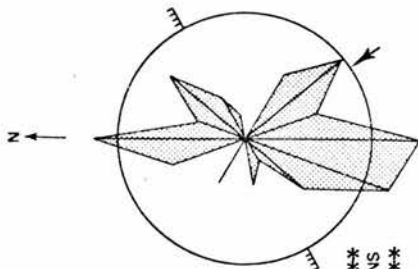
By far the best and most interesting section in the till ridges of this area is one 7 m high cut by Carsphairn Lane (10, Figure 7.3). The section showed two tills that displayed a complex relationship with one another (Figure 7.4, Plate III). This is the only location in the Carsphairn Lane valley where two tills were found to be exposed. The lower unit comprised a very tough, grey to dark-grey (5Y, 4.5/1), clay-rich till, which was exposed for a maximum of 2 m above the stream bed. Attempts to auger through this till to ascertain its total thickness had to be abandoned owing to its extremely tenacious and stony nature.

The grey till was overlain by the olive till mentioned previously and here comprised a sand/silt-rich deposit that was in places indurated, while elsewhere it was fairly friable. The upper parts of the olive till contained occasional sand-rich horizons, apparently lacking stratification. A thin (0.5 m thick) reddish-yellow iron-stained horizon near the top of the section probably represents the lower limit of postglacial weathering of the till.

Figure 7.4

Load structures in the olive and grey tills
by Lamloch House, Carsphairn Lane valley.

TILL FABRIC A



An 180 = 1402 **
An 360 = 0.3072 NS
L% = 36.61 **

Circle indicates 10% of observations

Direction of ice movement determined from striae and glacial erratics

Trend of ridge crest

n = 50 pebbles

Class interval - 20°

An 180 } An statistic
An 360 }

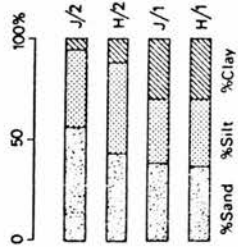
L% - Rayleigh test

** Significant 0.01 level

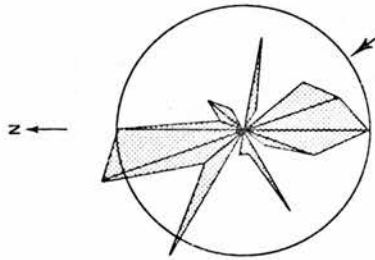
* Significant 0.05 level

NS Not significant

PARTICLE-SIZE ANALYSIS



TILL FABRIC B

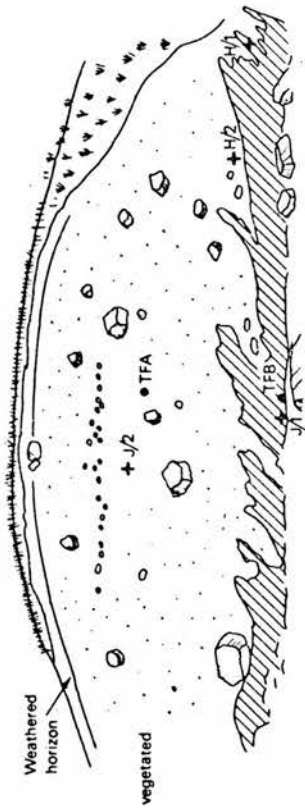


An 180 = 0.8266 *
An 360 = 0.1439 NS
L% = 27.53 *

SE.

Direction of Ice Movement

NW.



LAMLOCH TILL SECTION (NX 528965)
SHOWING LOAD STRUCTURES

- Till Fabric sites
- + Particle-size analysis sample sites
- Grey coloured till: (5Y 4.5/1)
- Olive coloured till: (2.5Y 4/4)



Plate III: Load structures in the grey and olive tills by Lamloch House (NX 528965). Ice movement from right to left. Metal rod 1 m long.



Plate IV: Subglacially engorged esker by Brockloch Farm (11, Figure 7.2).

The structural relationship between the two tills is complicated, with elongated "flames" of grey till apparently penetrating the olive till for distances of up to 1.5 m and at angles between 20° and 50° (Figure 7.4). These "intrusions" display a sharp contact with the contiguous olive till. Similar structures have been reported by Virkkala (1952) from eastern Finland, although the axes of the "flames" described by him were usually perpendicular. Examination of the prolate gravel-size clasts within each till on either side of the "flames" showed in many cases an alignment parallel to the margin of the "flame", indicating some form of thrusting or deformation of one till in relation to the other. Small lenses of grey till, up to 10 cm long, occurred in the olive till close to the "flames" and a similar pattern was observed with respect to olive till lenses. Particle-size analysis of the tills (Figure 7.4) showed that they are texturally different, even when samples from individual "flames" were analysed. Similar differences were found in the roundness, macro-fabric and lithological characteristics of the two tills.

These results indicate that the structures were not formed by weathering of the till (cf. Madgett 1975; Madgett and Catt 1978). It is suggested that the features are load structures produced by deformation of the tills in response to differences in the bulk density of the two tills (Anketell et al. 1970; R. Anderton, pers. comm. 1979). The deformation in the Lamloch section is not, however, symmetrical. If these features had been developed on a horizontal surface then it would have been expected that they would have had vertical axial planes (cf. Virkkala 1952). The axial planes of the load structures at Lamloch, so far as can be judged from two-dimensional

viewing, are inclined (between 20° and 50°) towards the SE. This implies that the deforming force was operating from anywhere within the arc to the NW $\pm 90^{\circ}$. As the trend of the load structure axes appears to be against the direction of former ice movement in the area, as shown by striae and erratics, the deforming force could not have been the over-riding ice. Differential loading by overlying stagnant ice, although capable of producing deformation structures (Boulton 1971) does not explain the trend of the load structures. A third possibility is that the valley slope, which is inclined towards the SE, provided the necessary environment to trigger deformation. Banham (1975) has noted that slopes of only $1-2^{\circ}$ can promote deformation structures of this type in till deposits.

Certain other conditions must also be met before the trigger mechanism can convert the initial metastable condition of the tills into a deformable one. This is particularly important in the case of tills because of the varied nature of their particle-size characteristics. High percentages of silt will tend to lower the porosity of the deposits and their susceptibility to liquefaction and deformation (R. Anderton, pers. comm. 1979). As a result:

- (a) both tills would have to have been water-soaked. The increased porewater pressure would have tended to promote deformation as the yield strength of the materials would have been much reduced (Terzaghi and Peck 1967).
- (b) the deformation would most probably have occurred soon after deposition of the tills, for increased compaction under their own weight, over a long period of time,

would have tended to increase the density of the tills (especially the grey till) and thus make them less susceptible to deformation.

It is suggested that the above conditions would most likely have been met at a time immediately after deposition of the tills or during final melting of the ice-sheet in the area. At this time large quantities of water would have been available to saturate the tills and thus promote their deformation. The structures have not evolved further since during the process of deformation water escape would have halted their development.

Only a limited number of glacial landforms composed of sand and gravel occur in the Carsphairn Lane valley. SE of Brockloch Farm (11, Figure 7.2, Plate IV) is a steep-sided (over 20°) esker-like ridge 8 - 10 m high and 350 m long. The ridge is slightly sinuous with an undulating crest-line, is aligned perpendicular to the valley axis and descends the valley side from 220 m to 190 m O.D. Small linear ridges with associated dead-ice hollows occur immediately to the SE of the main ridge. A large section (NX 541956) in the latter, 8 m high, revealed loose sand and gravel but its slumped nature made it impossible to determine whether the deposit was stratified. Abundant cobble-size clasts, predominantly of greywacke or shale, showed only limited signs of water-rounding. Roundness analysis (Powers 1953) of 100 clasts between -4 and -8 ϕ diameter showed that 35 per cent were angular, 46 per cent sub-angular and 19 per cent sub-rounded. This result, however, may be partly explained by the characteristic slab-like form of greywacke clasts, which is not conducive to the production of well-rounded shapes. The sand-rich

nature of the deposit, as well as its differentiation from the olive till, was demonstrated by particle-size analysis, the results showing 90 per cent sand, 5.4 per cent silt and 4.6 per cent clay.

By Drumjohn Farm a small esker (12, Figure 7.3) curves down the valley side from ca. 240 m to 220 m O.D. Small exposures showed sub-rounded to sub-angular gravels composed mainly of greywacke. The most extensive area of sand and gravel lies SW of Meadowhead Farm (Figure 7.3) where a complex of fluvio-glacial deposits occur on the valley floor at ca. 210 m O.D. This complex comprises a flat-topped mass of sand and gravel (175 m x 100 m), which has the appearance of a kame delta (13, Figure 7.3). The feature is about 10 m high and possesses steep ice-contact slopes on three sides, although the west-facing slope has undoubtedly been trimmed by the waters of Carsphairn Lane. The fourth side of the kame merges into the lower slopes of Lamford Hill at ca. 220 m O.D. Closely associated with this feature are two eskers, which are gently sinuous and possess slightly undulating crest-lines, a small kame and a series of dead-ice hollows. Poor exposures in these landforms, including one in the flanks of the esker marked 14 in Figure 7.3 (NX 517987), showed coarse sand and gravel. The majority of the clasts were sub-angular or sub-rounded and composed of greywacke or shale. Several boulders of granite up to 0.7 m in length were embedded in the surface of the feature.

Finally, another esker was mapped by the eastern shores of Loch Doon (15, Figure 7.3). This feature is more subdued (3 - 4 m high) than the others in the area, but has a pronounced winding course and a gently undulating crest-line. A small quarry in its western end (NX 505995) showed a well-rounded, quartz-rich, pea-gravel with very few cobble-size clasts. No stratification was observed owing to slumping.

The fluvioglacial deposits described above have several features in common.

- 1) They all commence on the lower slopes of the west-facing side of the Carsphairn Lane valley and terminate abruptly at the central part of the valley floor.
- 2) They are all aligned west or SW, a trend that is perpendicular to the direction of former ice movement in the area and parallel with the orientation of the cross-valley ridges.
- 3) They do not occur above ca. 240 m O.D.
- 4) They appear to merge (with the exception of esker 15) into the till-covered hill slopes and show no sign of linking with meltwater channels.
- 5) They are confined to the area of ground between the former ice-shed (see Chapter 5) and the present-day watershed.
- 6) The eskers do not possess the same sinuosity or length that is characteristic of many esker forms described in the literature.

The above evidence suggests that the eskers are of the "subglacially engorged" type described by Mannerfelt (1945) and Sissons (1958b).

Characteristically these forms occur on valley sides where meltwaters have entered the ice from a lateral position (cf. Sissons 1958a).

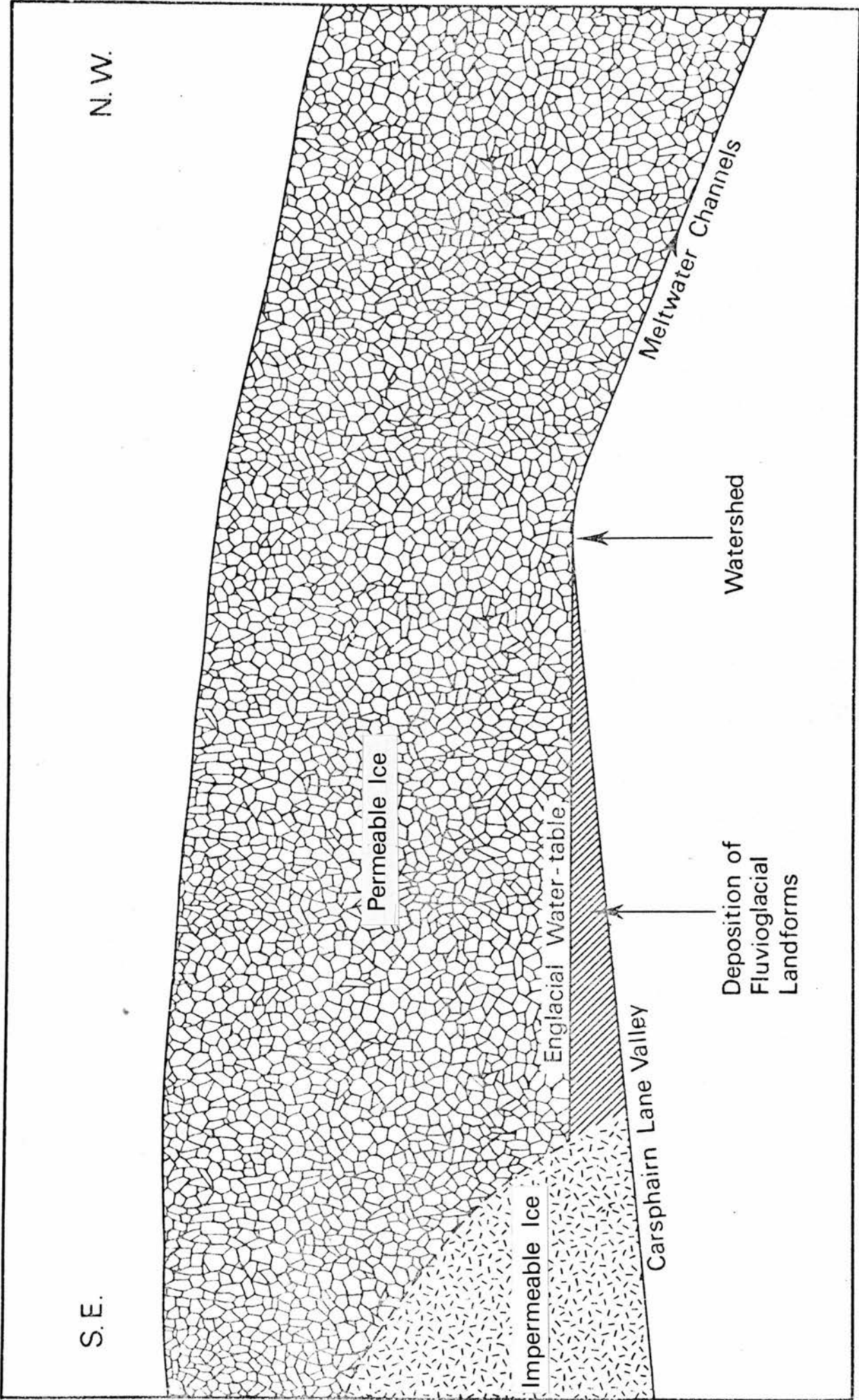
Also they tend to be shorter and straighter than normal eskers (Sugden and John 1976) and are usually formed at an advanced stage of ice disintegration when their alignment is controlled by local topography rather than by the regional ice surface gradient.

As the fluvioglacial deposits only occur between the former ice-shed and the present watershed it is probable that the latter

functioned as a barrier to the free flow of water from south to north. It is therefore suggested that a considerable volume of water was held up within the ice on the southern side of the watershed. Such an arrangement implies the presence of an englacial water-table within the ice, impounded towards the SE by impenetrable ice farther from the margin (Figure 7.5). Below the water-table deposition of fluvio-glacial deposits would have been promoted as meltwater flow would have been retarded. This interpretation is supported by the upper ends of the eskers (as well as the flat-topped kame) all lying within the altitudinal range 220 - 240 m. When the eskers were being formed the upper limit of deposition was controlled by the col now occupied by part of Loch Doon (and feeding into channel 3). That meltwaters once occupied this col is shown by esker 15. This col is the lowest point in the watershed of the Carsphairn Lane valley. Its present floor altitude is uncertain owing to the presence of the loch. However, soundings made by Murray and Pullar (1910) indicate that the altitude is ca. 200 m, the bedrock floor presumably being lower. As this control could only have operated through the ice itself, extensive ice decay is implied. Moreover, since the englacial water-table was unable to fall below the altitude of the Loch Doon col, the level at which it intersected the valley at any time was approximately the upper limit of sand and gravel deposition.

It seems likely that the earlier outlets for the meltwater were channels 1 and 2, which have intakes at 295 m and 260 m O.D. respectively. The absence of depositional landforms related to these intake levels suggests that when these channels were being formed an englacial water-table did not exist. Later the Loch Doon col replaced

Figure 7.5 Diagram showing relationship between englacial water-table and fluvioglacial erosion and deposition in the NW part of the Carsphairn Lane valley.



channels 1 and 2 as the outlet, the meltwaters being able to flow with increasing freedom through the ice as decay progressed and deposition of sand and gravel ensued. The later occupation of the Loch Doon col by meltwaters is indicated by a difference in height of some 8 m between channel 2 and channel 3 at their confluence (Figure 7.1B).

The concept of an englacial water-table controlling the deposition of fluvioglacial landforms also helps to explain their absence from the remainder of the Carsphairn Lane - Water of Deugh - River Ken valley. To the SE of the former ice-shed by Carsphairn the absence of any topographic barrier that might have impounded meltwaters means that they would have had a relatively unrestricted flow in that direction. Meltwaters were probably concentrated beneath the ice along the line of the present streams, merely cutting restricted channels below the general level of till deposition. Such an explanation would also account for the excellent preservation of the cross-valley ridge landforms in this area.

(iii) The area surrounding the Craig of Knockgray Hill mass.

The glacial deposits in the valleys of the Water of Deugh (north of the Green Well of Scotland, NX 557946), Benloch Burn and Polsue Burn and on the west and SW slopes of Craig of Knockgray are different from those described in sections (ii) and (iv). In the former areas massive deposits of till with a valley-fill morphology cover the valley-side slopes and floors (Figure 7.6, Plate V). The till has been incised by streams to give a "valley-in-valley" cross-profile. It is of variable thickness, reaching a maximum of at least 18 m along the axis of the Water of Deugh valley by its confluence with Polsue Burn (NX 563961). Away from the valley axes the till thins rapidly



Plate V: Valley-fill deposits of the Water of Deugh valley NE of the Green Well of Scotland.

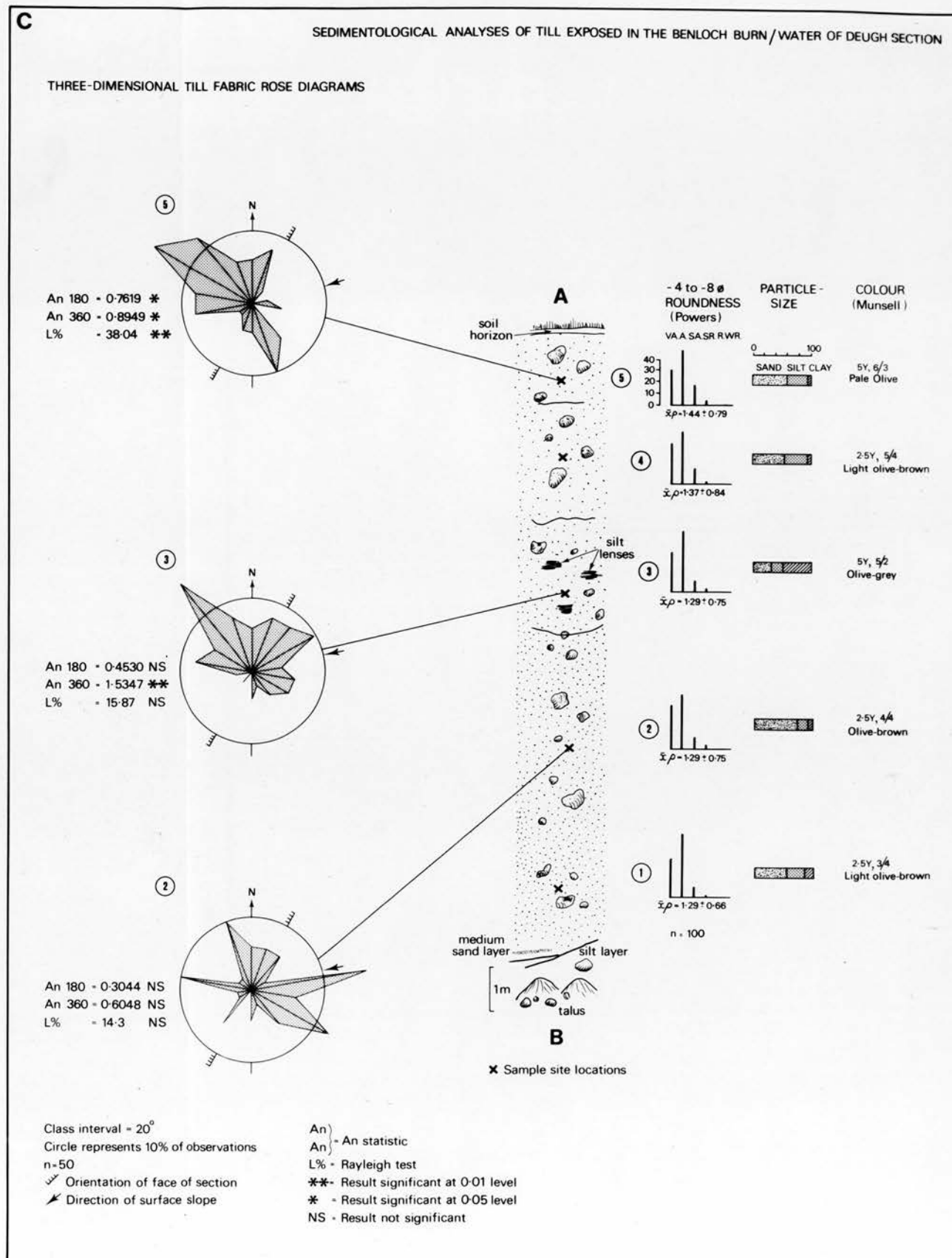
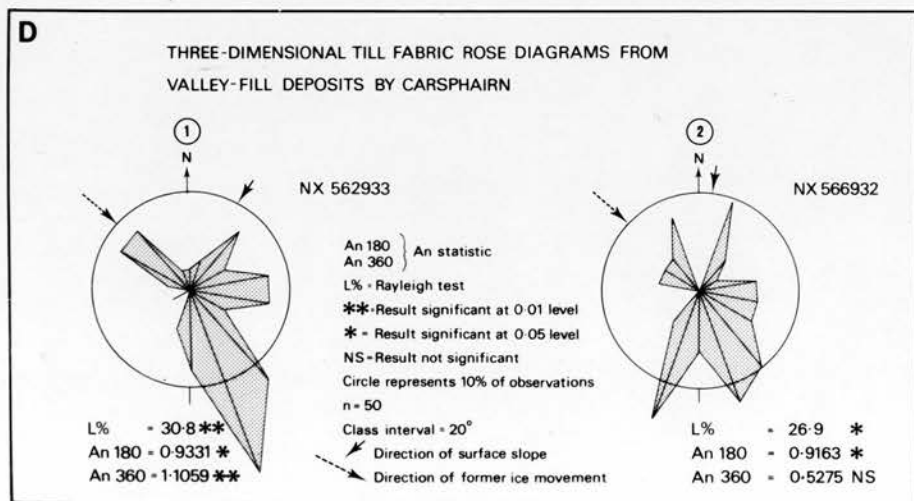
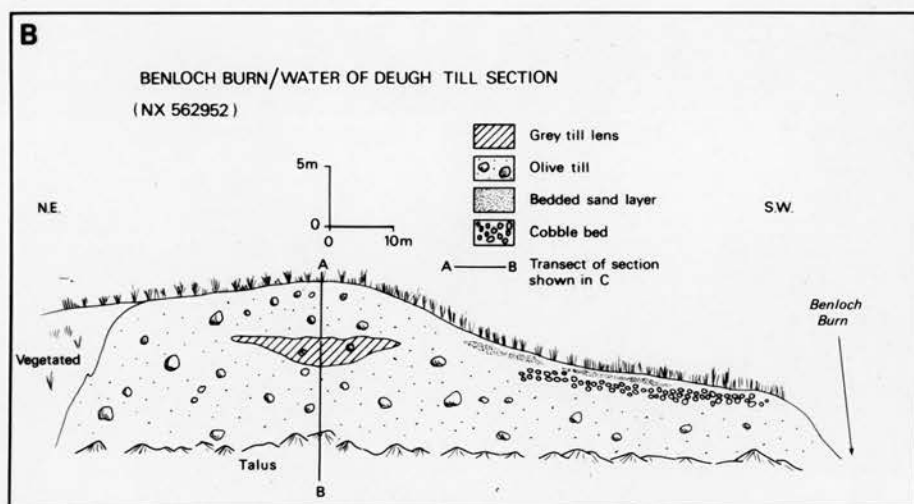
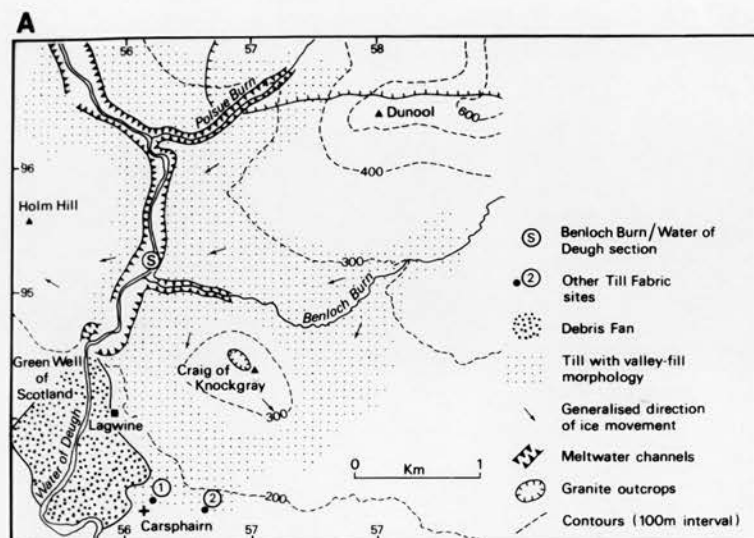


Plate VI: Benloch Burn - Water of Deugh section in valley-fill deposits. Lag deposit in the foreground.

Figure 7.6

**Valley-fill deposits by Craig of Knockgray
(section (iii), Chapter 7);**

- A. Distribution of valley-fill deposits by
Craig of Knockgray;**
- B. Sketch of till and other deposits exposed
at the Benloch Burn - Water of Deugh
confluence;**
- C. Results of sedimentological analyses on
the till exposed at the Benloch Burn -
Water of Deugh confluence;**
- D. Till fabrics from other sites within the
valley-fill (for locations see A).**



against the adjacent hill slopes at altitudes between 300 and 350 m.

In all except one of the exposures examined in these deposits the till was olive-brown (2.5Y, 4/4) in colour. Numerous large boulders (up to 0.8 m in length) and cobbles of greywacke, with fewer numbers of granite, occurred in a silt/sand-rich matrix. The contained greywacke clasts were largely angular, while those of granite were invariably sub-rounded. At no point was the till seen to rest on bedrock, so the maximum thickness of the till in the central parts of the valleys remains unknown. The till is sufficiently indurated and compacted to be capable of forming stream-cut bluffs up to 18 m high.

Similar deposits have been described by Price (1963) from Peebles-shire, E-C Southern Uplands, but in his study area the till is extensively covered by fluvioglacial sands and gravels. No such covering was observed in the many sections examined in the Craig of Knockgray area. Using criteria such as the compactness of the till and the presence of subglacially-formed meltwater channels, Price concluded that the deposits had accumulated subglacially.

The till deposits on the SW slopes of Craig of Knockgray show an interesting and important relationship to the cross-valley ridges. By the floodplain of the Water of Deugh near Lagwine House (Figure 7.7) are elongated ridges between 5 and 10 m high orientated SW-NE (perpendicular to the valley axis). Towards the NE these features merge into the gently undulating bench-like morphology of the valley-fill till that blankets the slopes of Craig of Knockgray below 280 m O.D. Contrastingly, to the SW the ends of the ridges are sharply truncated. A similar truncation is seen in the deposits immediately

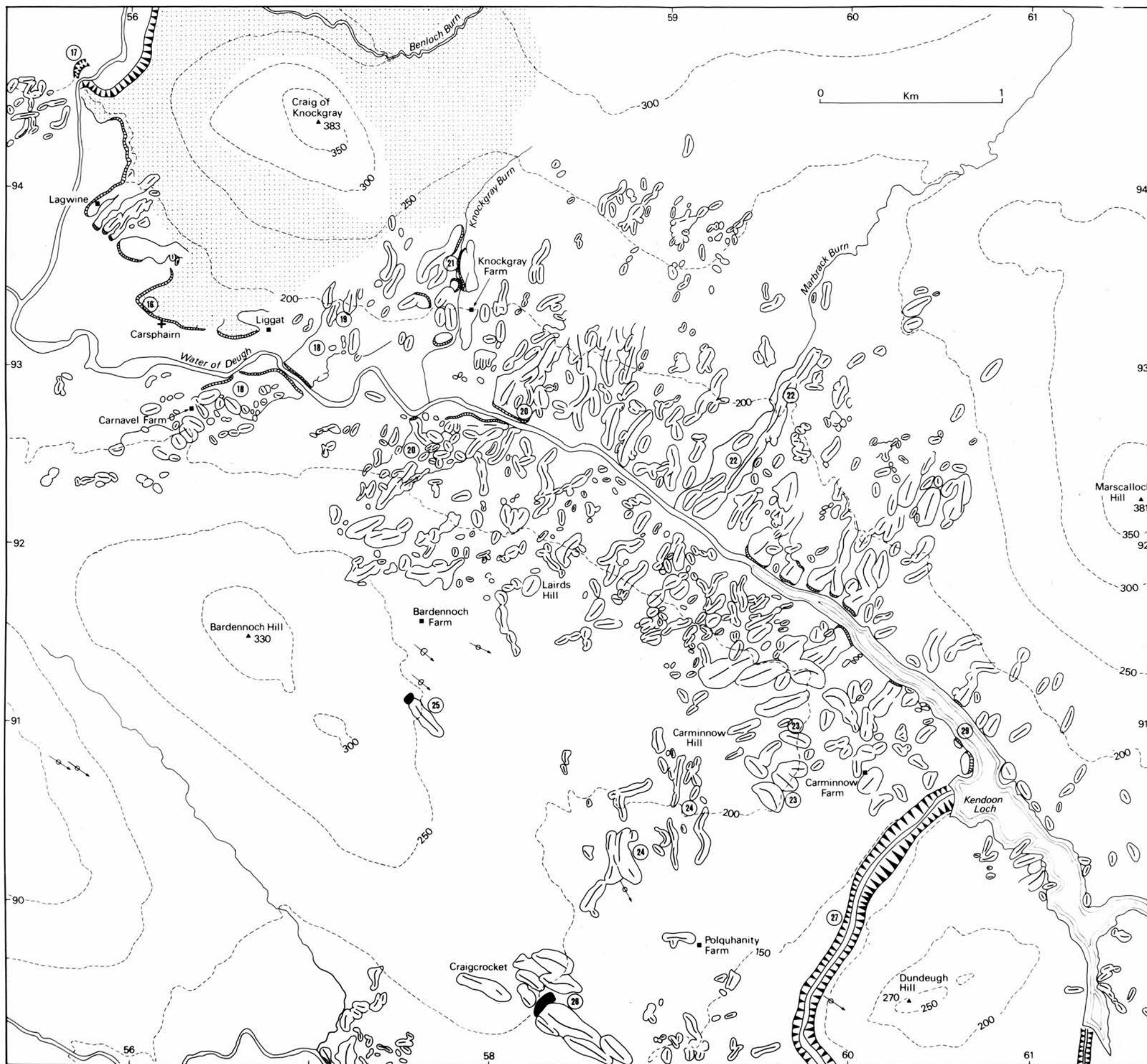
to the north of the ridges as well as to the SE, behind the village of Carsphairn (16, Figure 7.7). At these two locations, till with valley-fill morphology (with no ridges present) forms steep bluffs up to 5 m high bordering the floodplain.

The extensive truncation of the till landforms seems to be related to the large debris fan that here covers the floor of the Water of Deugh valley (Figure 7.6A). Its apex is near to the bedrock gorge from which the Water of Deugh issues SW of Green Well of Scotland. The fan has a surface area of just over 1 km². Small riverbank exposures (NX 560931, NX 546936) revealed a basal, very coarse, unstratified deposit consisting almost entirely of rounded greywacke and Cairnsmore of Carsphairn granite cobbles. This was overlain by 0.5 m of silt-rich alluvium containing gravel-size particles in the lower 10 cm. The sequence was capped by a layer of peat of variable thickness.

As the valley-fill deposits appear to show a relationship with the cross-valley ridges, it was decided to examine them in some detail. In addition an attempt was made to determine whether the valley-fill is a primary deposit or the product of mass-wastage (cf. Price 1961, Baker 1976). The investigation was greatly facilitated by two excellent exposures in the area. One of these is located by the confluence of Benloch Burn and Water of Deugh (NX 562952, Figure 7.6A). Being actively undercut it provided a fresh but very steep face (in places exceeding 80°). The till was exposed over a horizontal distance of ca. 200 m and reached a maximum of 14 m in height, the basal 1 m being concealed by slumped material (Plate VI).

The section showed a complex of tills (Figure 7.6B). The basal

Figure 7.7 Glacial landforms of the area between Craig
of Knockgray and Dundough Hill (section (iv),
Chapter 7). Key as for Figure 7.3.



10.2 m comprised a homogeneous till that was very tough and compact in places, probably owing to the relatively high silt content of the matrix. Other parts of the till, where the matrix was rather more sandy, were less indurated. Large boulders of greywacke, with subordinate numbers of Cairnmore of Carsphairn granite, were abundant throughout. The mean roundness value for the clasts between -4 and -8 ϕ lay in the "angular" class of Powers (1953), while the colour of the till varied from light olive-brown (2.5Y, 3/4) to olive-brown (2.5Y, 4/4) (Figure 7.6C).

The lowest 2 m of this till exhibited certain features indicating that water may have played a part in its deposition. A 4 cm thick horizon of medium- to fine-grained sand and a thin (2 cm) band of fine sand and silt, showing minute laminations, occurred in close juxtaposition and extended for 3 m along the base of the exposure. These horizons were generally sub-horizontal, but in one place the silt and sand layer bifurcated and one stratum climbed through the section for a distance of 0.5 m before dying out. The bands showed no sign of having been disturbed or faulted.

In the central, and highest, part of the section a large lens of olive-grey (5Y, 5/2) till lay within the upper 2.5 m of the above-mentioned olive till (Figure 7.6B). The contact between the two tills was sharp, in places undulating, but never deformed. Cobble- and gravel-size clasts straddled the contact without signs of disturbance. This lens was overlain by a light olive-brown (2.5Y, 5/4) till, which possessed similar textural and roundness properties to that examined beneath the grey till lens (Figure 7.6C). Indeed, where the grey till was absent any line of contact between the

two olive tills was impossible to define. The lens of grey till extended for a horizontal distance of 35 m along the face of the exposure and reached a maximum depth of 2.5 m. It was of variable composition and toughness, ranging from a hard, clay-rich till to a fairly friable, sandy material containing numerous gravel-size clasts of greywacke. In addition, "pods" of grey, laminated silt were present and these appeared to terminate against stiff, olive-brown (2.5Y, 4/4) deposits rich in silt and clay but unlaminated: the latter, however, did contain minute bands of fine-grained sand. Particle-size analysis shows the grey till to contain 47 per cent clay compared with an average of 16 per cent for the surrounding till. The roundness characteristics of the -4 to -8 ϕ clasts, however, show no difference from those of the ^{other} tills in the section, the mean value falling in the "angular" class of Powers (1953).

The exposure was capped only over a horizontal distance of 25 m (Figure 7.6B) by a fairly indurated, pale olive (5Y, 6/3) till possessing a high percentage of gravel-size material set in a gritty matrix. Elsewhere this till had been removed by meltwater erosion of the upper part of the section. This till also contained lenses of fine- to medium-grained sand as well as cobbles and boulders of greywacke and Cairnsmore of Carsphairn granite. The roundness and textural properties of this till are similar to those of the underlying olive till yet they have a sharp, linear contact. The till reached a maximum thickness of 1.5 m in the central part of the section.

One till fabric was sampled from each of the three main identifiable units in the exposure. The results are presented as three-dimensional rose diagrams, along with roundness and particle-

size analysis results, in Figure 7.6C. The fabric 5.3 m from the base of the section has a major mode approximately parallel with the direction of former ice movement in the area as shown by the distribution of Caradocian conglomerate erratics. However, two well-developed secondary modes complicate the result and statistical analysis (using the A_n statistic and Rayleigh tests: see Chapter 11 for detailed discussion) indicates that the distribution of the fabric is not significantly different from either a uniform or a random distribution. One fairly clear feature, however, is the lack of correspondence between fabric modes and the direction of maximum surface slope of the adjacent hill side. Similar results were also obtained from fabrics sampled 8.3 m and 13.2 m from the base of the section: only one fabric (fabric 5) was statistically significant but the diagrams show major modes approximately parallel to the former direction of ice movement and perpendicular to the maximum surface slope (Figure 7.6C). These limited observations seem to indicate that the till is a primary glacial deposit and not a product of mass wastage. This interpretation accords with the conclusions of Galloway (1958, 1961b) and Tivy (1962) from the Southern Uplands, who suggested that although till was soliflucted from the hill slopes and concentrated in the valley bottoms immediately after ice-sheet decay, the period was too brief for extensive volumes of material to be involved.

There remains the problem of the depositional environment of the till. The presence of thin silt and sand horizons as well as the grey till lens seem to argue for a supraglacial origin for these deposits. However, although the presence of small-scale water-laid

deposits indicates that water was present during deposition of the till it is not necessarily a criterion for suggesting that the whole deposit was formed supraglacially. Such structures were not found in any of the other till exposures examined in the Carsphairn Lane - Water of Deugh - River Ken valley. In addition, Simpson (1961) and Muller (1977) have indicated that changes in the abundance of water at the depositional interface can lead to lodgement tills developing lenses and pockets of sorted sediment. Dreimanis (1976) has also recorded laminae of silt and sand, representing melted layers of ice poor in debris, from subglacial melt-out tills.

The grey till lens, which is laminated in places, has some of the characteristics of an infilled kettle hole when viewed in two dimensions, but the absence of deformation or collapse structures between it and the olive till is not in accord with ice melt-out (cf. Maizels 1977). Moreover, if the area of the lens had been occupied by a block of ice then some indication of its former presence might be expected. The linearity of the upper contact of the grey deposit as well as the ground surface above the exposure show no sign of having been lowered by the melting of an ice block. It is also difficult to envisage the lens having been formed by deposition in a lake in a supraglacial environment and then covered by flow till, for the upper contact remains undeformed and no intercalations of one till within the other were observed along this contact as would have been likely if the olive till had flowed across what would have originally been a fairly soft surface.

A more reasonable explanation is that the material was formed during a brief period of sedimentation within a small subglacial pond

impounded while the tills were deposited. Certainly water had been available earlier as evidenced by the small-scale sand and silt horizons recorded from the basal parts of the exposure. Such an arrangement would account for the laminations observed in the deposit as well as the similarity in the roundness characteristics of the grey and olive tills, the clasts in the former being dropstones. The absence of deformation structures would also be explained, for there would have been no melting-out of blocks of ice or movement of one deposit in relation to the other. Finally, the deposition and preservation of laminated deposits in a subglacial environment is not unusual and examples have been reported by Shaw (1971), Sugden and John (1976) and Maizels (pers. comm. 1978).

In addition to the till analysed and described above, two other deposits were exposed in the section (Figure 7.6B). These comprised a bed of very fine- to medium-grained sand ca. 0.5 m thick (overlain by peat) showing ill-defined cross-bedding structures. This deposit rested directly on a coarse, cobble-rich horizon, up to 1 m thick, that was totally lacking in fines, except where in contact with the overlying sand. The coarse layer had the appearance of a "pavement" or lag concentrate and rested with marked unconformity on the olive till below. The former deposit comprised cobbles of greywacke generally between 8 cm and 25 cm in diameter, which were angular to sub-angular in shape and showed only slight signs of having been "washed".

The two deposits occupy a gently sloping bench that has been cut into the southern edge of the valley-fill till (parallel to the Benloch Burn) and lies ca. 5 m above stream level. This terrace-like form truncates all the olive tills described above (Figure 7.6B).

Similar features, cut into the valley-fill, lie at approximately the same altitude farther north, on the eastern banks of the Water of Deugh. These "flats" indicate partial dissection, probably by meltwaters (see below), of the valley-fill after deposition. Further, the close association of the sand and cobble horizons with the terrace-like features suggests that they also were related to this incision. As the lithology of the cobbles is similar to that of the underlying till it is probable that their concentration is attributable to erosion by meltwater of the underlying till (cf. Flint 1971). The cobbles would have concentrated by a combination of (a) fines being washed away from the original till and (b) deposition of clasts carried from farther upstream by meltwater. The overlying cross-bedded sands probably represent deposition during the waning phases of meltwater activity.

A second phase of incision into the valley-fill deposits is indicated in this area. The deep incision of the valley-fill deposits by the Water of Deugh and Benloch Burn has been referred to above. It is suggested that this incision represents the courses of former meltwater streams and that they are now occupied by the present drainage system as misfit streams. This view is supported by two lines of evidence.

- 1) An unequivocal meltwater channel is located on the lower, SE-facing slopes of Holm Hill, by the Green Well of Scotland (NX 557946) (17, Figure 7.7). The feature is cut entirely in bedrock to a depth of 6 m and lacks a stream. Since its northern intake is confluent with the deep incisions into the valley-fill farther up-valley,

a relationship between the two sets of landforms is indicated.

- 2) The present rate of erosion of the till bluffs fronting the Water of Deugh was estimated by Kirkby (1967) to be of the order of 15 mm/1000 years. If this is taken as a reasonable representation of conditions during the Postglacial, the massive incision achieved by the Water of Deugh and other streams cannot be attributed to the Postglacial. Since Loch Lomond Advance glaciers occupied certain valley heads in the Deugh basin (Holden 1977), meltwater from these may have contributed to valley-fill dissection. However, these glaciers were small: hence major erosion by meltwaters during ice-sheet decay seems to be implied.

It is concluded from the above that the valley-fill materials were deposited either from an englacial position or subglacially and were subsequently dissected by meltwaters from the decaying Late-Devensian ice-sheet, and that the river cliffs represent the remnants of meltwater courses that have been slightly modified by postglacial fluvial action.

The second main exposure examined in the valley-fill was in the village of Carsphairn (Figure 7.6A, NX 562993). Excavations associated with extensions to the village hotel provided a fresh section 2.2 m high, the lower 1.7 m of which comprised a very indurated, sand-rich (over 70 per cent), pale olive (5Y, 6/3) till. Boulders and cobbles of greywacke were common throughout the section, with a mean roundness value in the "angular" class of Powers (1953).

Occasional gravel-size clasts of porphyrite, dolerite and rotted granite were also present. As described from the tills in the Carsphairn Lane valley (section (11)), open-work lattices of coarse sand were a feature of the material surrounding the cobble-size clasts. A till fabric 0.5 m from the base of the section showed a major mode trending 20° E of S (Figure 7.6D), which parallels the direction of former ice movement in the area as shown by erratics. The major mode is almost perpendicular to the direction of maximum surface slope, which again suggests that the till is a primary deposit. The upper 0.5 m of the exposure comprised a friable, gravelly horizon with a sandy matrix, whose contact with the underlying till was sharp and undulating. This layer had a "washed" appearance and may therefore be related to mass-wasting processes reworking the original till, possibly during the Loch Lomond Stadial, although there is no evidence of this. It is also possible that the horizon may be related to the upper till in the section by the Benloch Burn - Water of Deugh confluence, but the two deposits differ in particle-size and degree of induration. The upper 0.2 m of the exposure in Carsphairn was weathered to a yellowish-red colour, with soil structures present in the top 10 cm.

ESE of the above exposure, a pit was excavated in deposits forming a continuation of the valley-fill (Figure 7.6A, NX 566932). This revealed an indurated, stony till with a silt/sand-rich matrix, light olive-grey (5Y, 6/2) in colour: the deposit also showed reddish mottling in places owing to gleying processes and this may also have affected the original colour of the till by the release of manganese. Greywacke cobbles were very common and had a mean roundness value in

the "angular" class of Powers (1953). A till fabric from this location showed a bimodal distribution. The relationship between these modes and the former direction of ice movement and direction of maximum slope are shown in Figure 7.6D. One mode seems to parallel ice movement, while the other trends in the direction of maximum slope, thus making interpretation of the fabric inconclusive.

Finally, small sections were cleared in the truncated faces of the cross-valley ridge extensions of the valley-fill by Lagwine House (Figure 7.7) mentioned above (NX 558936 and NX 558938). Both showed the same kind of deposit, namely an olive till (5Y, 5/3), which was in places indurated (where it was silt-rich), while in others it was fairly friable (the sand-rich parts). Boulders, invariably of grey-wacke and up to 0.3 m in length, were abundant, the clasts between -4 and -8 ϕ being characteristically angular in shape. Again an open-work lattice of coarse-grained sand particles surrounded many of the cobble-size clasts. The till fabric from the above-mentioned section is discussed in Chapter 11 along with other fabrics from the cross-valley ridges.

Discussion of the significance of the morphological relationships between the valley-fill and cross-valley ridges is deferred until the end of section (vii) of this chapter, for valley-fill and associated cross-valley ridges were also mapped in the Garryhorn valley (section (vii)) and that part of the River Ken valley NE of its confluence with the Water of Deugh (section (v)). Analysis of the sedimentological properties of the tills comprising these landforms is considered in Chapters 8, 9 and 10.

(iv) The area between Craig of Knockgray and Dundough Hill.

This section of the Carsphairn Lane - Water of Deugh - River Ken valley is occupied by the Water of Deugh stream and it is here that the cross-valley ridges are best developed (Plate VII).

SE of Carsphairn village a pronounced cross-valley ridge extends SW-NE completely across the valley (18, Figure 7.7; Plate VIII) except where cut by the Water of Deugh. Bedrock is exposed in the river bed between the two parts of the ridge. SW of the river beyond Carnavel Farm the ridge merges into a drift-blanketed hillside at ca. 200 m O.D. An indurated olive till is exposed in small sections, but numerous bedrock knolls protrude through the thin drift veneer. Farther NE the ridge becomes impressive, reaching 15 m in height and 200 m in width by Carnavel Farm. Here the SE-facing slope is steep (15° - 20°) and adjoins a low undulating area of peat through which knobs of bedrock project. The upper surface of the ridge comprises interlinked elliptical or oval-shaped mounds that appear drumlinised. The crest-lines of these mounds are generally orientated NW-SE, which is transverse to the overall trend of the ridge but parallel to the direction of former ice movement. Similar features have been referred to by Prest (1968) from the Boyd Lake area, N.W.T. in Canada, where they have been recognised as characteristic of ribbed moraine. Similarly Lundqvist (1969b) has described Rogen moraines from northern Sweden that possess drumlinised upper surfaces.

A pit 1.8 m deep was excavated at NX 568929, where the ridge is at its widest (250 m). Below 0.7 m of made ground, 0.4 m of till showing signs of weathering and soil development was exposed, passing into 0.3 m of fairly friable, stony till with a gritty matrix. The



Plate VII: Cross-valley ridges SE of Carsphairn village (looking NW).

Note valley-fill deposits on the flanks of Craig of Knockgray.



Plate VIII: Large ridge (18, Figure 7.7) traversing the Water of Deugh valley SE of Carsphairn village. Ice movement from left to right.



Plate IX: Large ridge (20, Figure 7.7) traversing the Water of Deugh valley SE of ridge 18. Ice movement from right to left.

lowest 0.4 m comprised an unweathered light olive-grey (5Y, 6/2) till, which became increasingly indurated and silt-rich with depth. The toughness of this till was demonstrated by the fact that the mechanical excavator used to dig the pit was unable to penetrate below 1.8 m. Small roadside sections in the same ridge (NX 569929; NX 569928) showed till similar to that exposed at the base of the pit. This was tough, silt-rich and light olive-brown (2.5Y, 5/4) and in places had a reddish-brown mottling due to gleying.

NE of the Water of Deugh the ridge changes character, becoming flat-topped and reaching a maximum of 200 m in width and 12 m in height. Above ca. 190 m O.D. elongated ridges up to 120 m long and 3 - 4 m high are superimposed on the main ridge (19, Figure 7.7). These are generally orientated N-S, but farther upslope (above 220 m O.D.) they parallel the trend of the main ridge. Also at this point the slopes defining the main ridge become obscure and merge into the till-covered slopes of Craig of Knockgray, which possess a valley-fill morphology (see section (iii)). This part of the ridge has morphological affinities to the adjacent valley-fill with its broad and flat-topped shape. There is no evidence to suggest that the ridge has been formed by dissection of a formerly more extensive valley-fill deposit. It therefore appears that a change in depositional conditions within the ice was beginning to alter the type of landform produced and that the major ridge is transitional between the two types.

Some 500 m SE of ridge 18 a second large ridge completely traverses the valley (20, Figure 7.7; Plate IX). This ridge is more complex in its morphology and shows no direct links with the

valley-fill deposits. It comprises a steep-sided ridge-on-ridge form 20 m high at the point where it is cut through by the Water of Deugh. Bedrock is exposed extensively in the bed of the river at this locality. The superimposed ridges are usually linked by low swells and generally trend towards the valley axis, although certain of the forms are orientated oblique or perpendicular to the alignment of the main ridge. They are 4 - 8 m high and show considerable variation in length, reaching a maximum of 350 m (Figure 7.7).

Numerous, excellent roadside sections (NX 576923; NX 576924; NX 574925; NX 578926; NX 577923) in this ridge all showed an olive (usually 5Y, 5/3 or /4) till. The upper metre was normally quite friable and weathered, but the till rapidly became more indurated with depth. The latter was very stony with boulders up to 1 m in diameter not uncommon; these were usually set in a silt/sand-rich matrix.

Between the two major ridges (18 and 20, Figure 7.7), by Knockgray Farm (21, Figure 7.7), are ill-defined ridges 3 - 5 m high that have subdued cross-profiles. These features appear related to the valley-fill deposits mentioned above. In this case, however, certain of the "ridges" are the result of dissection by the waters of Knockgray Burn, as indicated on Figure 7.7. A riverbank section in one of these "ridges" (NX 578933) showed an indurated, olive (5Y, 5/3) till with a silty matrix below a friable, weathered till 0.5 m thick. On the SW side of the River of Deugh, between ridges 18 and 20, well-defined ridges up to 100 m long and with a cross-valley trend showed till of a similar type to that described above (NX 571926).

The cross-valley ridges attain their best development SE of the second major ridge mentioned above (20, Figure 7.7), particularly

NE of the Water of Deugh, where the valley-side gradient is fairly gentle (Plate VII). Over a distance of ca. 3 km elongated ridges, usually trending perpendicular to the valley axis, occupy this side of the valley. They vary between 20 m and 70 m in width and range in length from a mere 20 m to one ridge by Marbrack Burn (22, Figure 7.7) that extends continuously for 1.2 km. This is the most impressive ridge in the whole area. The ridges attain their maximum height (up to 15 m) at the valley axis and decline up-slope to merge into formless till that covers the hillside above 250 m O.D., although a few poor and much attenuated ridges occur above this altitude. If these latter features are included the upper limit of ridges in this section of the valley is 275 m O.D. A similar upper limit was observed in the Carsphairn Lane valley (section (ii)), which suggests that the ridge-forming process was only able to operate below this altitude. Another factor influencing ridge height is the "beaded" form of many of them, with each "bead" being linked to the next by a lower swell some 3 to 5 m high. The crests of the "beads" are typically smooth but the overall long-profile is undulating as a result of the intervening swells.

Extensive peat in the inter-ridge hollows makes the true height of many ridges greater than it appears to be (Figure 7.8). At one location (NX 587925) close to the valley axis 6 m of peat were found between two ridges. Upslope the peat thins to between 0.5 m and 1 m.

The ridges possess several common morphological characteristics.

- 1) Several show branching patterns (e.g. NX 585928; NX 584923; NX 587919).
- 2) Most of the ridges are linear features, although others are

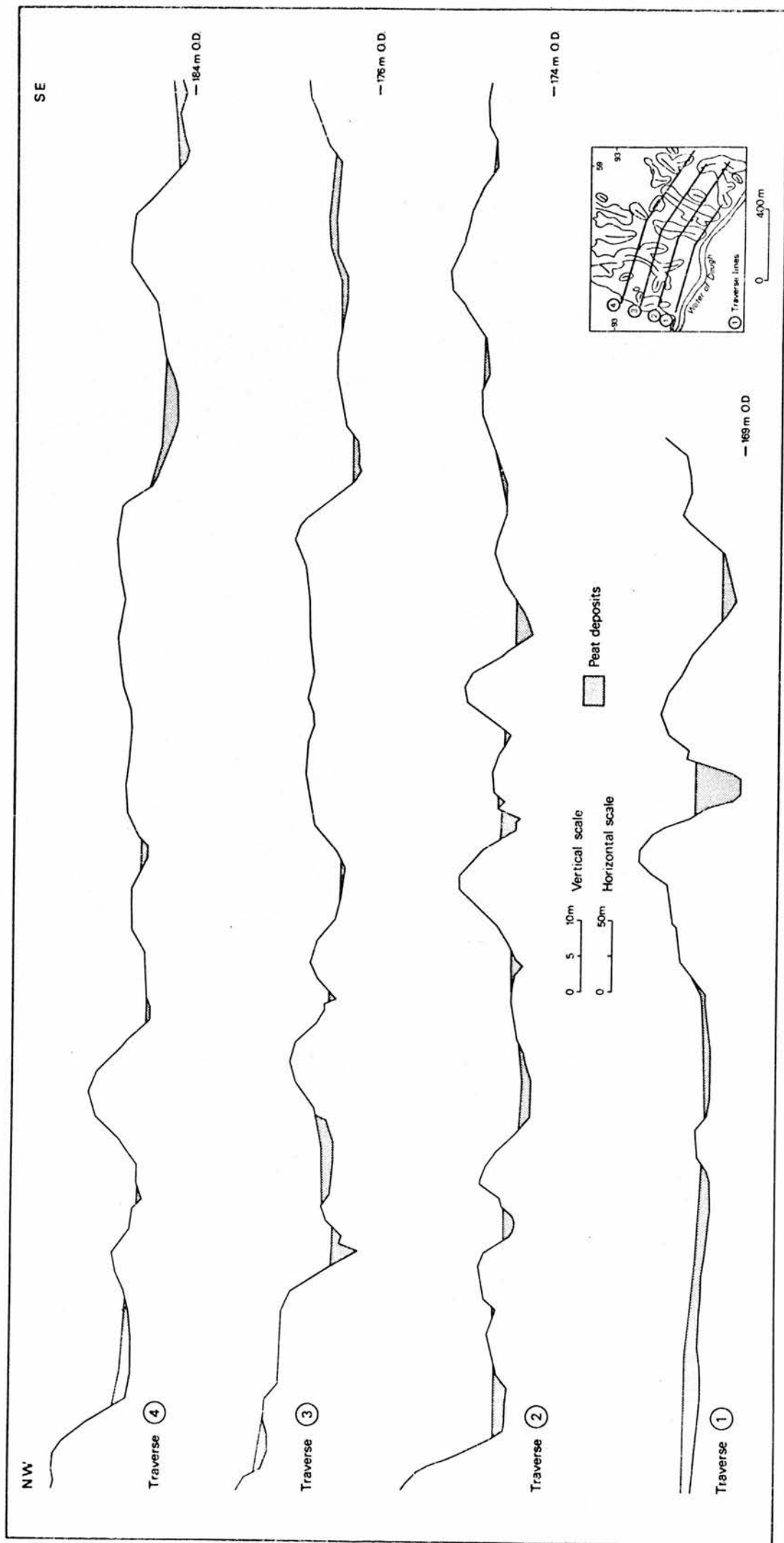
distinctly sinuous. Indeed, on the aerial photographs certain ridges have the appearance of eskers at first sight.

- 3) Unlike the two large ridges, 18 and 20, Figure 7.7, none of the others has equivalents on the opposite side of the valley. The ridges terminate abruptly at the valley axis and in many cases the ends of the ridges show signs of truncation, which appear to be unrelated to the present stream (Plate X).
- 4) The trend of the ridge crest-lines is generally NE-SW, transverse to the alignment of the Water of Deugh valley. As shown in Chapter 5 ice movement in this area was NW-SE, perpendicular to the trends of the ridges.
- 5) The cross-profile of the ridges is extremely variable, as shown by the surveyed profiles in Figure 7.8. Most commonly they are either symmetrical (with slopes varying between 5° and 20°) or the distal (SE-facing) slopes are steeper, reaching 25° - 30° in places.
- 6) The spacing between adjacent ridges also varies considerably, but in general is of the same order as their width.

Sections in the cross-valley ridges between ridge 20 and Dundee Hill are not abundant. However, the nine exposures that were examined (NX 591922; NX 592922; NX 596928; NX 597919; NX 608907; NX 607906; NX 586925; NX 588924; NX 603907) all showed a stony, generally olive till (ranging from 2.5Y, 5/4 to 5Y, 6/3). Boulders of greywacke, up to 0.8 m long, were set in a sand- or silt-rich matrix that became increasingly more indurated with depth. No stratified deposits were observed in any of the sections. Roundness analysis showed the clasts to be angular (see Chapter 10). Visually,

Figure 7.8

Surveyed cross-profiles of the cross-valley
ridges SE of Carsphairn village.



therefore, these deposits resemble those described from the sections in valley-fill as well as those from the ridges in the Carsphairn Lane valley.

Inter-ridge exposures of till were unavailable owing to thick peat accumulations, but the extensive outcrops of bedrock in both the beds of the Water of Deugh and Marbrack Burn suggest the inter-ridge till is thin. These bedrock outcrops and that one mentioned by ridge 18 were the only ones encountered in the vicinity of the cross-valley ridges in this part of the valley.

SE of ridge 22 (Figure 7.7), the cross-valley ridges become more massive and typically reach 100 - 150 m in width, although remaining the same in other respects. A similar change is also observable in the morphology of the ridges on the SW side of the Water of Deugh. By Carminnow Farm the ridges not only become more massive, but some take on drumlinoid characteristics. Although the majority continue to be aligned perpendicular to the valley axis, others (e.g. 23, Figure 7.7) trend NW-SE, parallel to the valley axis. The reason for this is not clear, but it may be partly related to the change in direction of valley-side slope (from NW-SE to NE-SW). Elongation of the ridges down this slope also occurs 800 m north of Polquhanity Farm (24, Figure 7.7). The "beaded" ridges exhibit both a linear and a sinuous pattern in plan, are 100 - 400 m long, 50 - 100 m wide and up to 8 m high. Some even possess an esker-like morphology, but roadside sections (e.g. NX 589901; NX 588902) and deep plough furrows in an adjacent forestry plantation revealed an indurated olive (5Y, 5/3) till.

The area between Laird's Hill and Carminnow Hill (Figure 7.7) is

dominated by thick peat that exceeds 7 m in places. Ridges may be present below the peat cover but no evidence is available. To the SW, however, (beyond the A713 road) peat is largely absent and till occurs only as sporadic hummocks 2 - 3 m high. The landscape is instead characterised by streamlined and ice-moulded landforms. Well-striated roches moutonnées (Figure 7.7) SSE of Bardennoch Farm and a large crag-and-tail (25, Figure 7.7) indicate NW-SE ice movement. A similar trend is shown by elongated drift tails located down-ice from a large bedrock knoll on the SE slopes of Craigcrocket (26, Figure 7.7).

By Dalshangan House (Figure 7.7) the till cover has thinned considerably and ice-scoured bedrock knolls are much in evidence. One roadside section (NX 594891) showed 1.5 m of olive till resting on 3 m of shattered bedrock, while in another (NX 598885) only olive till was exposed. A similar pattern is observable east of Dundough Hill, by Arndarroch Farm (Figure 7.7). Here the till cover is much attenuated, being characterised by randomly orientated ridges 2 - 3 m high. Striated bedrock knolls commonly protrude through the till indicating ice movement towards the SE.

The final features of note in this section of the valley are two large channels incised into both the western and eastern flanks of Dundough Hill (27 and 28, Figure 7.10). They are 2.2 km and 2.8 km long respectively and reach a depth of 25 m in places. These very impressive V-shaped gashes are largely cut in hard greywacke bedrock, although parts of the westernmost channel are cut in till (with a ridge morphology in places) that mantles the adjacent slopes. Sections in the latter revealed a tough olive till rich in greywacke

boulders and cobbles. Jardine (1959) suggested that this section of the valley represented a knickpoint in the long profile of the River Ken - Water of Deugh drainage system. The valley gradient certainly steepens considerably here, falling 45 m in 2.3 km, but the form of the channels and their deep entrenchment into bedrock is suggestive of erosion by meltwaters from the decaying ice-sheet.

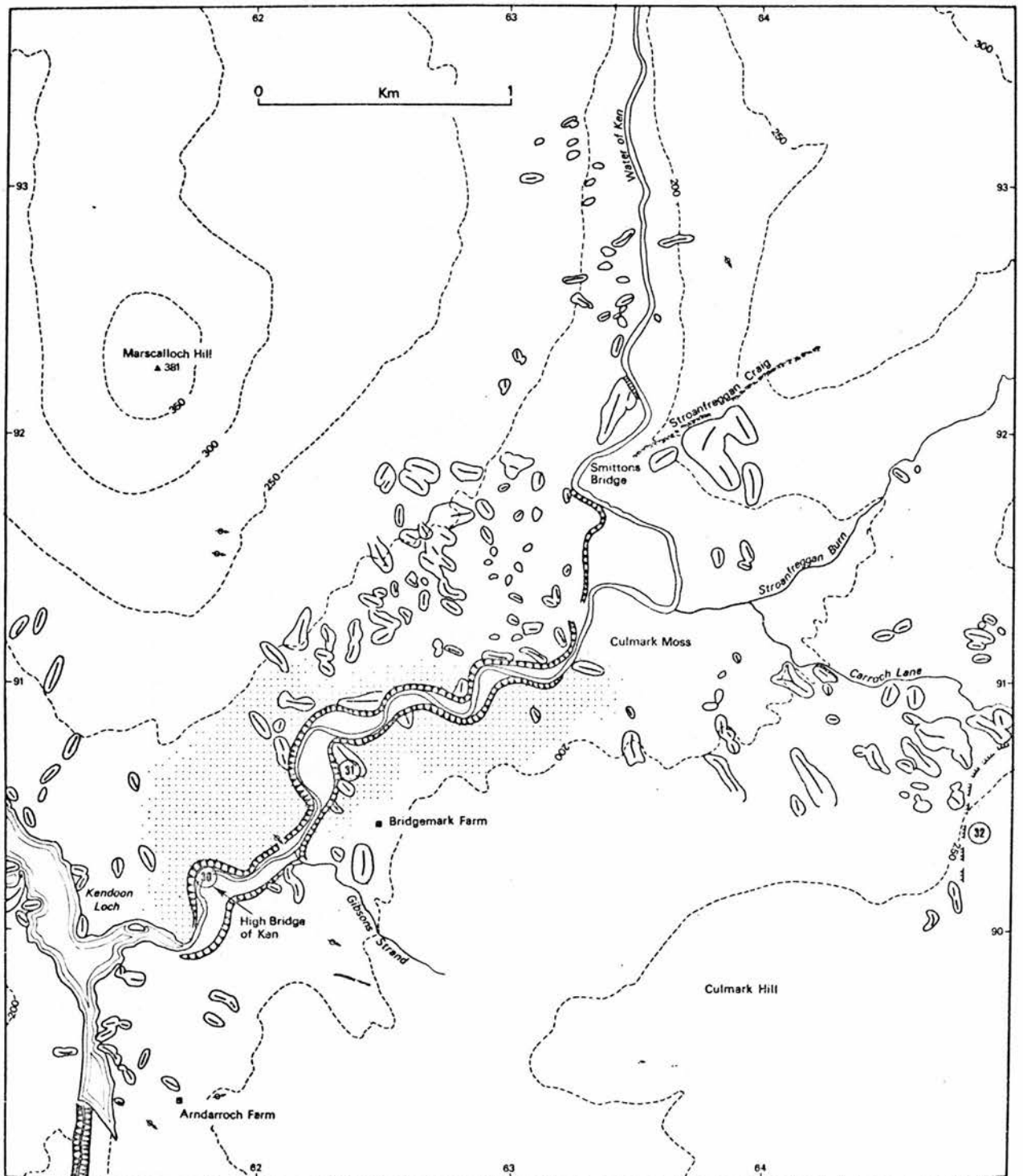
Any relationship between the channels and the cross-valley ridges farther to the NW could not be determined owing to the masking effect of the Kendoon reservoir. Examination of photographs of the area, however, taken prior to dam construction showed that the two channels are confluent and extend at least as far NW as NX 607908 (29, Figure 7.7).

- (v) The River Ken valley NE of its confluence with the Water of Deugh.

This part of the River Ken valley comprises two contrasting sections. The 2.5 km section above the Water of Deugh confluence is relatively constricted (0.8 km wide) and is orientated NE-SW. To the NE the valley widens to ca. 1.5 km and swings round to become orientated N-S. Striae and erratics indicate that the whole valley is aligned transverse to the direction of former ice-movement. It is suggested that these two factors have influenced the nature of the glacial landforms deposited in the area. These landforms (Figure 7.9) consist of valley-fill deposits that are in places related to drumlinoids and cross-valley ridges.

By High Bridge of Ken (NX 618902) thick till in the form of valley-fill blankets the south-facing slopes of Marscalloch Hill

Figure 7.9 Glacial landforms in the area NE of the
Water of Deugh - River Ken confluence
(section (v), Chapter 7). Key as for
Figure 7.3.



below 200 m O.D. At the centre of the valley the till forms impressive bluffs that attain a maximum height of 15 m. Here the River Ken flows on bedrock and shows no sign of actively trimming the till bluffs, which are heavily vegetated (30, Figure 7.9). At the confluence of Gibsons Strand with the River Ken (NX 620902), 2 m of indurated, grey (5Y, 5/1) till were exposed in the valley floor. The deposit exhibited a strong fissile structure and had a clay content in excess of 25 per cent. This till was recorded by Skae *et al.* (1877, p.40) as being a "tough boulder clay". Two metres higher in the bluff, a friable, olive (5Y, 5/3) till was exposed. The matrix was sand-rich and contained numerous angular clasts of greywacke. The nature of the contact between the two tills could not be determined owing to slumping. The stratigraphical arrangement, however, was the same as that described from the section by Lamloch House in the Carsphairn Lane valley (section (ii)), but here the tills occur in the form of valley-fill, while at Lamloch the sequence was displayed in one of the cross-valley ridges. The whole section is 8 m high, which gives a minimum thickness to the olive till of 4 m. To the SE the till thins rapidly and bedrock knolls protrude through this attenuated cover of drift, indicating localised deposition of thick till in the central part of the valley.

Ridge 31 in Figure 7.9 is 200 m long, 3 - 4 m high and appears to rest directly on the valley-fill deposits. This ridge and the three others adjacent to it have been sharply truncated at their NW-facing ends where they border the River Ken floodplain. A section in ridge 31 (NX 623908) showed 4 m of tough, clay-rich, grey (5Y, 5/1) till similar in all respects to the till exposed by Gibsons Strand. On the opposite side of the river ridges again occur on the upper parts

of the valley-fill. These generally trend NE-SW, similar to those mentioned above and parallel to the direction of former ice movement. Sections in the bluffs on the NW side of the River Ken showed a clay-rich, grey till up to 2.5 m thick, which was overlain by a fairly tough, sand-rich, olive till exceeding 3 m in thickness (NX 626910; NX 629911). The contact between the two tills was very sharp and linear. No deformation structures or transition zones were visible.

Away from the valley axis on the NW side of the valley irregular till ridges become more extensive, thus masking the characteristic valley-fill morphology described previously. Deep plough furrows and a small quarry in one of the ridges (NX 627914) revealed a tough, sand-rich, olive till (5Y, 5/3) containing boulders of greywacke and Cairnsmore of Carsphairn granite. The ridges have no clear pattern and in places resemble the hummocky moraine of Hoppe (1952). At ca. 220 m O.D., on the slopes of Marscalloch Hill they are replaced by a featureless till blanket.

The valley-fill morphology of the till also becomes less pronounced NE along the River Ken valley, the bluffs terminating by Culmark Moss (NX 632910) on the SE side and by Smittons Bridge (NX 633918) on the NW side (Figure 7.9). This coincides with the point at which the valley becomes wider. The valley-fill is replaced by till landforms of a more varied character and the till is much reduced in thickness. Most commonly the till forms elongated ridges, up to 200 m long, that occupy the floor and lower slopes of the River Ken valley as well as the valleys of its left bank tributaries (Carroch Burn and Stroanfreggan Burn) (Figure 7.9). Many of these ridges are drumlinoid and orientated NW-SE, parallel to the direction

of former ice movement. Elsewhere, till forms either irregular hummocks, some of which are bedrock cored, or a thin blanket covering the bedrock. Sections in the ridges in the Carroch Lane valley (NX 648910; NX 641911) showed an indurated, pale olive (5Y, 6/3) till with a silt-rich matrix. A high percentage of angular greywacke clasts was a notable feature of the till; Cairnsmore of Carsphairn granite erratics were also present. Till is absent above ca. 250 m O.D. on the northern flanks of Culmark Hill, where its termination is marked by a well-defined drift limit (32, Figure 7.9).

Till with valley-fill morphology reappears (on the extreme eastern edge of the field area) to the east of National Grid easting NX 655, where it occupies the central part of the narrow valley containing Stroanfreggan Burn. A stream-bluff section (NX 657922) showed 6 m of till, with the same dual sequence described previously. The lowest 1.5 m of the section comprised a fairly friable, clay-rich (33 per cent), dark grey (5Y, 4/1) till overlain by 4.5 m of very gritty (71 per cent sand), friable, olive-brown (2.5Y, 4/4) till. The contact between the two units was sharp and undulating.

In summary, the glacial landforms in this area possess distinctive characteristics. The thickest deposits of till are confined to the valley axis and are in the part extending 2.5 km upstream from the River Ken - Water of Deugh confluence. Here the till forms valley-fill with hummocks and elongated ridges, with a superimposed drumlinoid morphology in places. The till thins rapidly against the adjacent valley-side slopes, although a slight asymmetry in deposition is apparent, with till occurring at higher altitudes on the SE side of the valley than on the NW.

Two tills are exposed extensively in the bluffs bordering the River Ken floodplain: a silt/sand-rich, olive till rests with sharp unconformity on an indurated, clay-rich, grey till. The former usually constitutes the material forming the superimposed hummocks and ridges, except for one location (31, Figure 7.9) where only grey till was exposed. The grey till is confined to the valley-fill deposits, and where these are absent, so is the grey till.

This landform relationship in combination with the evidence from striae and glacial erratics (Chapter 5) permits certain inferences about the conditions of till deposition in the area. The erratics and striae show that former ice movement in this valley was generally NW-SE. Therefore, although the elongated ridges mentioned above trend across the valley, their long axes parallel the former direction of ice flow and this accounts for many of them possessing a drumlinoid morphology. Further, the presence of these forms superimposed on the upper surface of the valley-fill indicates that it was deposited subglacially before ice activity ceased. The River Ken valley in this area is perpendicular to the direction of former ice movement. This is in direct contrast to the area occupied by the cross-valley ridges (section (iv)), where ice moved parallel to the valley trend. It is suggested, therefore, that the trend of the Ken valley as well as its narrowness provided conditions that promoted the deposition of till with a valley-fill morphology. A similar situation has been described by Sissons (1976) from the Tweed basin. Here ice moved across valleys aligned perpendicular to ice movement and thick deposits of till occur on valley floors and lee slopes. Also Mangerud (1965), Bergerson and Garnes (1972) and Garnes (1973) have

described the same type of arrangement in the Gudbrandsdal area, E-C Norway, as has J. Lundqvist (1970) from NW Sweden. In the Water of Deugh valley NE of Green Well of Scotland (section (iii)) the same pattern is again apparent. Transverse valleys would have increased effective pressure in the ice and thus promoted till deposition in these locations (cf. Boulton 1975a). In addition the upstanding hill mass of Marscalloch Hill on the northern side of the River Ken would have protected any deposits in its lee slopes from subsequent removal.

It is clear, therefore, that the glacial landforms in the River Ken area show distinct differences from those in the Deugh valley SE of Carsphairn village (section (iv)), but they possess certain affinities with those in the Deugh valley north of Green Well of Scotland (section (iii)). The till of which the landforms are composed, however, is similar. This is especially so with the olive till in terms of texture, induration, stoniness and colour (see Chapter 8 for further discussion). The grey till equates well with that exposed by Lamloch House in the Carsphairn Lane valley, but differs from that found at the Water of Deugh - Benloch Burn confluence in its lack of lamination structures.

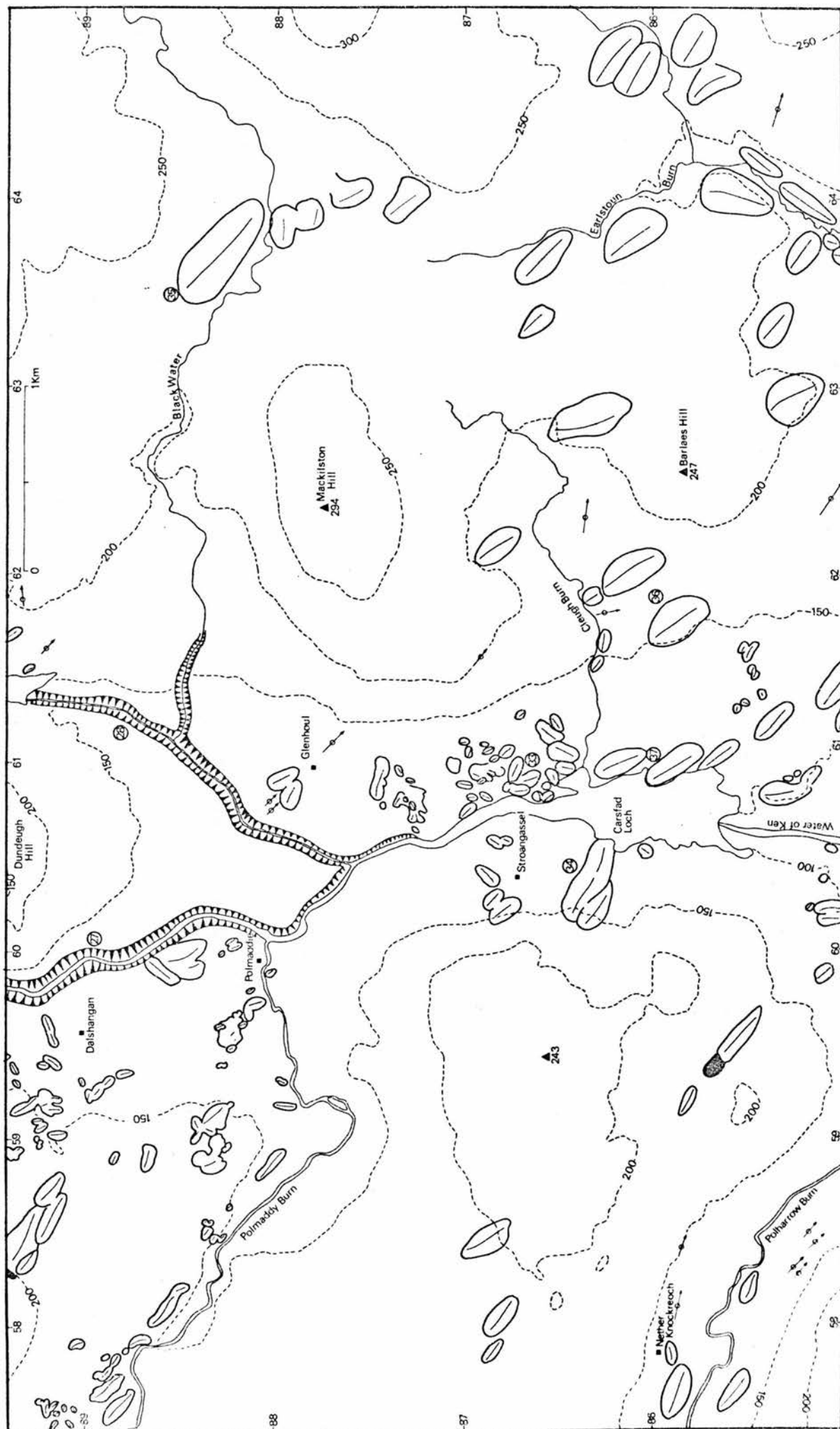
Finally, the valley-in-valley cross-profile of the River Ken valley NE of the confluence with the Deugh, produced by fluvial incision into the valley-fill, is identical to that described from the Water of Deugh in section (iii). Following from the discussion of these features on pp.139-140, it is inferred that the incision in the River Ken valley was also due to meltwater erosion. The close association between the latter forms and channels 27 and 28 by Dundee Hill supports this interpretation.

(vi) The area between Dundough Hill and New Galloway.

In the northern part of this area, between the termination of channels 27 and 28 and where Cleugh Burn enters Carsfad Loch (Figure 7.10), the glacial landforms continue those described in section (iv). The floor of the River Ken valley is occupied by irregular hummocks 3 - 8 m high, some of which are elongated (up to 150 m in length) but show no regular cross-valley trend (33, Figure 7.10); their "confused" morphology is suggestive of hummocky moraine. Numerous sections examined in these features (e.g. NX 606875; NX 599879; NX 603863) all showed a stony, olive (5Y, 5/3) till with a silt-rich matrix that became increasingly more indurated with depth. The last above-mentioned section is in a massive double ridge (34, Figure 7.10) that extends for 500 m upslope from the western shores of Carsfad Loch. It is 10 m high, has a smooth, rounded crest-line and is unique in this part of the River Ken valley in that it possesses a cross-valley trend. This trend is also oblique to former ice movement as shown by striae and ice-moulded landforms. The ridge appears to mark a definite change in conditions of till deposition, for to the south of it drumlinoids, and then classic drumlins, become the dominant feature. No drumlins occur to the north of ridge 34 in the main River Ken valley, although they are present in the valleys to the east. One particularly good example in the valley of Black Water is 600 m long and 15 m high (35, Figure 7.10).

Immediately south of Cleugh Burn and ridge 34 drumlinoid landforms increase in abundance, but they are poorly formed, flat-topped and generally less than 5 m high (e.g. the two drumlinoids located west of Barlaes Hill; 36, Figure 7.10). These features trend NW-SE

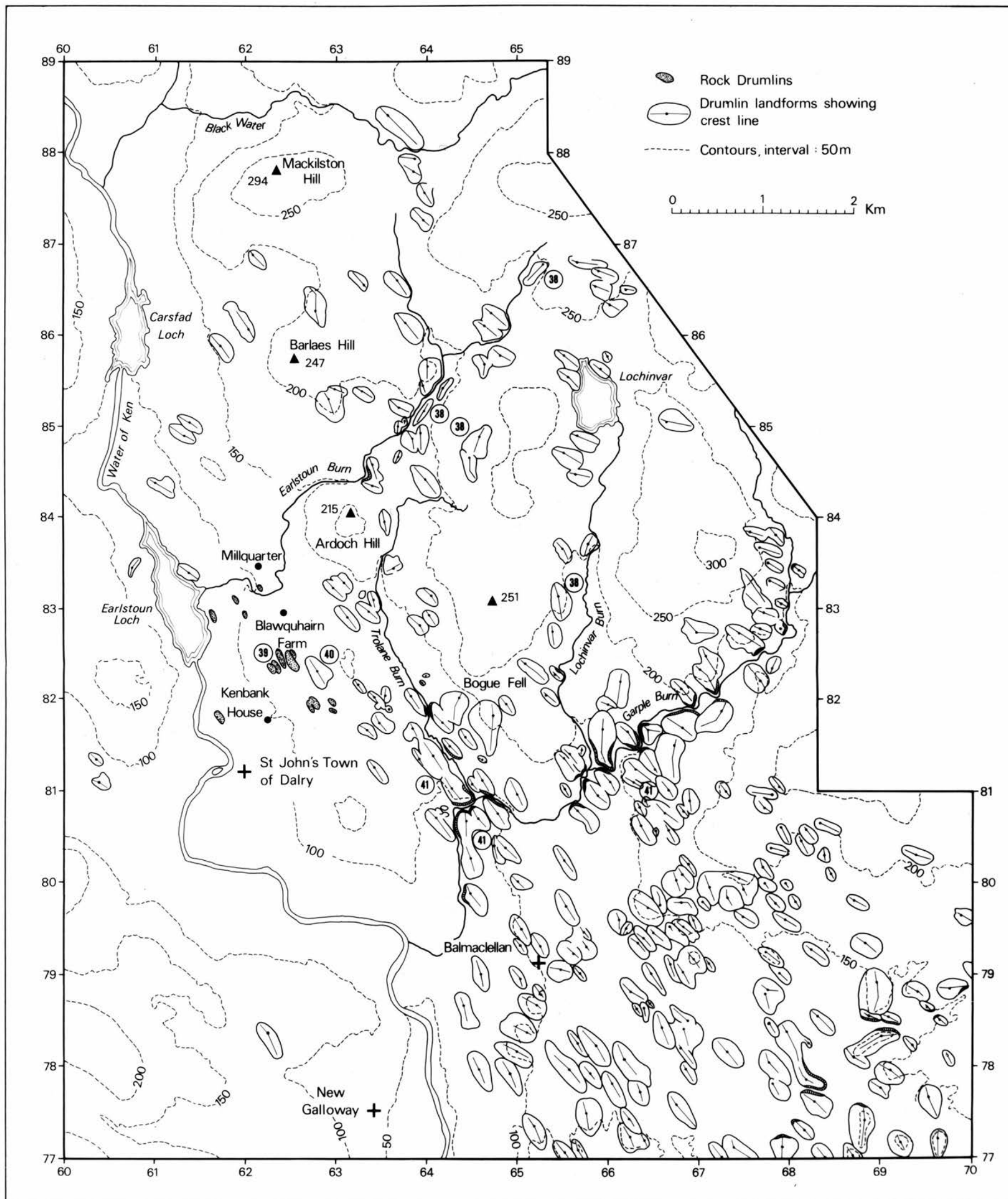
Figure 7.10 Glacial landforms in the area between Dundough
Hill and Carsfad Loch (section (vi), Chapter 7).
Key as for Figure 7.3.



indicating that the direction of ice movement was oblique to the alignment of the valley, which is here N-S. The composition of these features was revealed in several exposures (e.g. NX 608861; NX 615834) all of which showed an olive-brown (2.5Y, 4/4 to 6/2), stony till whose matrix was sand-rich (over 50 per cent) and poor in clay-size particles (less than 10 per cent). The first mentioned section, in the stoss end of a drumlinoid located on the eastern banks of Carsfad Loch (37, Figure 7.10) also contained significant percentages of cobble-size greywacke clasts. The ground surrounding the drumlinoid landforms has a thin veneer of till (0.5 to 1 m) through which ice-scoured knolls of bedrock commonly protrude. It is thus possible that some of the drumlinoids may be bedrock cored, although no evidence for this is available.

A contrasting series of landforms occurs to the east of Barlaes Hill in the narrow valley occupied by Earlstoun Burn. The valley floor and sides are covered by a suite of well-defined drumlins, as in the basin farther to the east containing Lochinvar (Figure 7.11). Numerous exposures in these forms (e.g. NX 645857; NX 656855; NX 647858; NX 634845) revealed an indurated olive (2.5Y, 4/4) till with a sand-rich (over 50 per cent) matrix that contained greywacke boulders up to 1 m in diameter. The drumlins vary in length, but average 350 m, and reach a maximum height of 20 m. They normally trend NW-SE, but several forms are aligned NW-SW, parallel to the orientation of the valley (38, Figure 7.11). A similar trend occurs in certain of the drumlins in the valley of Lochinvar Burn (38, Figure 7.11). The close juxtaposition of landforms indicating two different directions of ice flow is problematical. It is possible that the drumlins

Figure 7.11 Glacial landforms in the River Ken valley
between Carsfad Loch and New Galloway.



trending NE-SW may be related to a later, small-scale, phase of ice movement when local relief was a more important factor controlling ice flow and till deposition (cf. Rose and Letzer 1977).

Between Earlstoun Loch and St John's Town of Dalry in the Ken valley the till cover is limited to a very thin veneer that rarely exceeds 0.5 m, while in places it is absent. Ice-scoured bedrock knolls abound and in certain locations have been streamlined into impressive rock drumlins. This is particularly so in the area 500 m south of Blawquhairn Farm (39, Figure 7.11), where rock drumlins averaging 200 m in length, with one 12 m high, indicate intense sculpturing by ice. Skae *et al.* (1877) and Charlesworth (1926a) considered the "moraines" by Millquarter (Figure 7.11) to be the southern continuation of the cross-valley ridges located by Carsphairn village (section (iv)). Yet landforms composed wholly of drift, except in one instance, do not exist in this area. Ridges are present but these are rock drumlins and moutonnée forms with a covering of olive till generally less than 0.8 m thick.

The one example of a depositional landform in this landscape dominated by ice erosion is an isolated drumlin, with text-book form, 600 m SSE of Blawquhairn Farm (40, Figure 7.11). Its crest-line is typically asymmetrical, the highest point being some 20 m above the surrounding ice-moulded terrain. An exposure in the flanks of this feature (NX 627823) showed an indurated yellowish-brown (10YR, 5/6) till with a silt/clay-rich matrix.

By Kenbank House (Figure 7.11) moutonnée bedrock forms, with classic asymmetrical long profiles, are well developed and show evidence of strong ice gouging. The trend of both landforms and striae indicates NW-SE ice movement. In this area deposits of till are confined

to intervening bedrock hollows (cf. Nobles and Weertman 1971), while to the west by Allangibbon Cottage (NX 616822) rock drumlins with a thin till veneer are the characteristic landform. The trend of these features mirrors the ice flow pattern found farther north.

In the valley immediately to the east, occupied by Trolane Burn, quite different landforms appear. Here well-defined till drumlins occupy the complete width of the valley floor as well as the lower slopes of Bogue Fell (Figure 7.11). They show great variety in both width (50 - 300 m) and length (100 - 600 m) and reach a maximum height of 20 m. Many possess the typical drumlin asymmetry with the highest point normally lying near the NW end while to the SE the ground falls away gently in a tapering tail. Similar forms also occupy the valley of Garple Burn and the southern end of the valley of Lochinvar Burn (Figure 7.11). One characteristic of the drumlins in these locations is the tendency for two or three of them to merge, thus forming a composite feature (41, Figure 7.11). These composite forms in no way resemble the "superimposed" or "megadrumlins" described by Rose and Letzer (1977) from the Glasgow and Eden valley areas. In fact no examples of these latter features could be found in the areas mapped by the present writer, which suggests that these landforms may exist only in the subjective eye of the individual researcher.

The predominant trend of the drumlins in the Trolane Burn valley is NW-SE which is parallel to the valley axis. In the Garple and Lochinvar Burn valleys, although the alignment is still NW-SE (with some of the forms in the upper reaches of Garple Burn swinging round to WNW-ESE), the trend of the valley is perpendicular to this orientation.

This arrangement suggests that the roughness of the glacier bed is an important factor controlling till deposition (see below).

One of the most interesting relationships is rock drumlins and moutonnée bedrock forms, indicating ice erosion, in close juxtaposition to drift drumlins, which imply large-scale lodgement of till. A second, and probably interlinking, correlation is the restriction of well-defined drumlins to the narrow valleys (Earlstoun, Lochinvar, Trolane and Garple) lying east of the River Ken valley. Similar arrangements have also been described by Embleton and King (1975) from the Eden Valley and by Sissons (pers. comm. 1978) from the Tweed drumlin field.

Without speculating on the mechanisms of drumlin formation, several inferences may be drawn from the above field observations concerning the preferred locations for drumlin deposition. The major trend of ice movement in this southern part of the River Ken valley was NW-SE. This would not only have been supplied by the major ice stream flowing from the former ice-shed zone by Carsphairn (Chapter 5), but also by ice flowing SE from sources on the eastern flanks of the Rhinns of Kells range via the Polmaddy and Polharrow valleys. This additional input of ice may have increased ice velocity in the River Ken valley and thus have promoted erosion (as opposed to deposition). The power of these "tributary" ice streams is evidenced by the impressive ice-moulded bedrock landforms and by the change in ice-flow direction in that part of the valley south of Dundough Hill, from a trend parallel to the valley axis to one oblique to it. It seems likely that in the valleys to the east of the River Ken valley ideal conditions obtained for lodgement till to be

deposited in the form of drumlins. Here relief enhancement would have increased effective pressure on the subglacial bed, which resulted in a decline in the rate of abrasion and then deposition of the till. In addition the valleys may also have acted as subglacial escape routes for porewaters in the till during its deposition, again increasing effective pressure, as the impermeability of the greywacke bedrock would not have allowed groundwater escape.

South of St John's Town of Dalry drumlins become more abundant and cover both valley and interfluve alike (Figure 7.11). This distribution, however, is largely a reflection of the underlying relief, which is more "open" and undulating than that farther north (generally less than 150 m altitude). These drumlins form the NW part of the extensive Galloway - Solway drumlin field proper and indicate a SE regional ice flow.

Unfortunately sections in these features are comparatively rare, but by the village of Balmaclellan road improvements exposed several excellent sections. One exposure (NX 651787), 10 m high, showed a very tough, homogeneous, yellowish-brown (10YR, 5/4) till with a clay content of over 30 per cent. Very few cobble-size clasts were present and no boulders. The till also exhibited a well-developed platy structure that paralleled the surface of the feature. Contrastingly, immediately to the west by the A713 - A712 road junction (NX 645783) cuttings showed that three drumlins possess bedrock cores covered by 1 - 2 m of clay-rich till. These observations show that some of the drumlins at least are bedrock cored, although the exact number is impossible to estimate owing to the scarcity of good sections.

(vii) The Garryhorn Valley.

The Garryhorn Valley is a W-E-trending U-shaped trough with a gently sloping gradient to its floor in the eastern part. The valley varies in width from 500 m in its western section to just over 1 km where it joins the Carsphairn Lane - Water of Deugh - River Ken through valley (Figure 7.2). In direct contrast to the landforms of glacial deposition described from other parts of the through valley (sections (ii) to (vi)), this valley displays a complex arrangement of landforms that comprise both cross-valley ridges and dissected valley-fill.

The valley head is occupied by landforms interpreted as having been formed during the Loch Lomond Stadial (Chapter 13 and Figure 13.1). Immediately east of the Loch Lomond glacier limit five massive till ridges, that extend for 850 m down-valley, occupy the valley floor and sides below 300 m O.D. (Plate XI). Above 300 m the ridges become ill-defined and merge into an amorphous blanket of till. The till cover terminates on the southern side of the valley at a sharp drift limit at ca. 350 m O.D. The three westernmost ridges are the most impressive and stand in marked contrast to the delicate Loch Lomond Advance terminal moraine (Figure 7.2, Plate XI). They vary in height from 12.5 to 4 m and their basal width ranges from 125 m to 60 m. The largest ridge (42, Figure 7.2) extends for 800 m as a continuous feature (except where cut by Garryhorn Burn) on both sides of the valley.

Two surveyed cross-profiles of the ridges on the northern side of the valley (Figure 7.12) show a marked W-E decline in amplitude. Further, they indicate no regular spacing to the ridges. The absence



Plate X: Cross-valley ridge showing abrupt termination of the Water of Deugh valley axis.

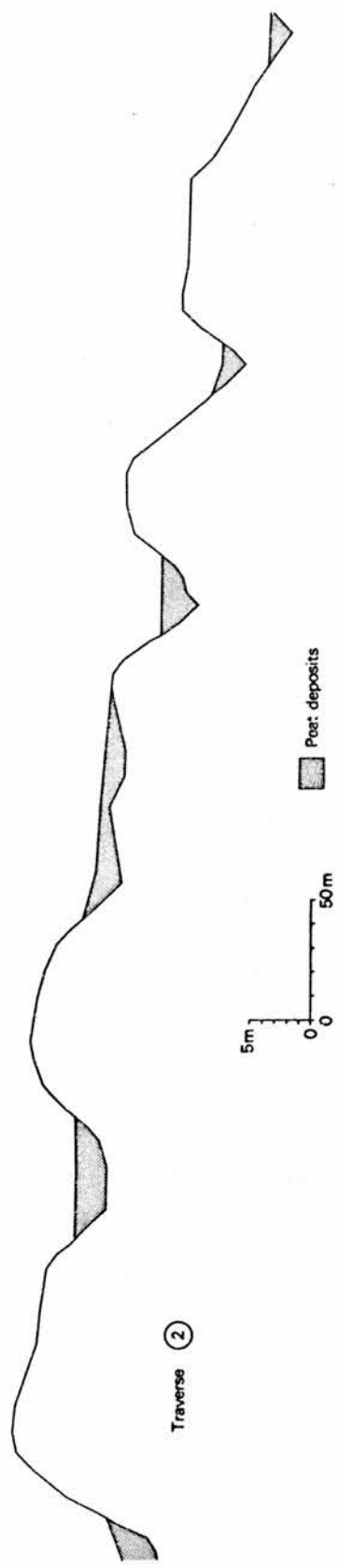
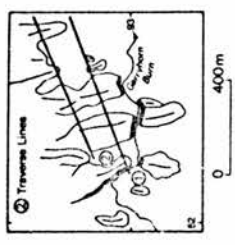


Plate XI: Large cross-valley ridges in the western part of the Garryhorn valley. Landforms associated with two Loch Lomond Advance glaciers (glaciers 10 and 11, Figure 13.3B) can be seen in the background occupying the valley-head.

Figure 7.12 Surveyed cross-profiles of the cross-valley
ridges in the Garryhorn valley.

WSW
NX 52229310

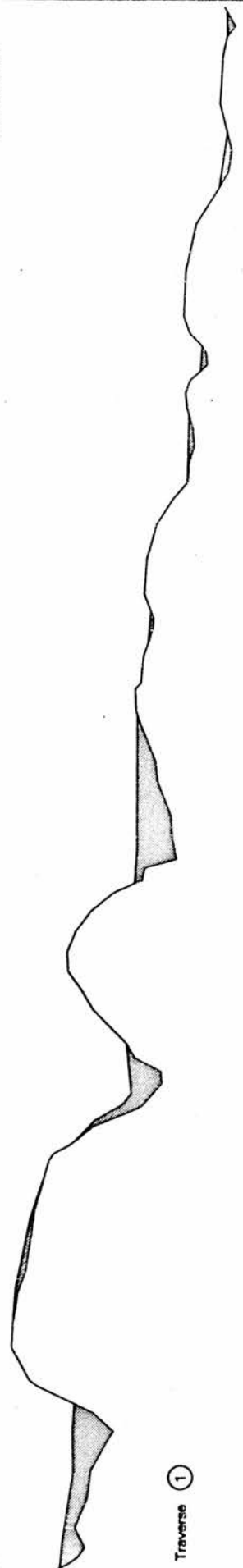
ENE
NX 52589319



WSW
NX 52199303

ENE
NX 52589314

Garphom
Burn



of bedrock outcrops in this section of the valley and the thin inter-ridge peat (a maximum of only 3.8 m having been measured) suggests that substantial amounts of till may be present below the ridges. Since the ridges merge into massive valley-fill deposits farther east (see below) it seems likely that the former represent the surface expression of more extensive accumulations of valley-fill. All the ridges are orientated N-S, perpendicular to the alignment of the valley. Striae, the Caradocian conglomerate erratics train and the Loch Lomond Advance glacier limits all indicate that the general trend of ice flow was W-E, transverse to the ridge trends.

The three largest ridges have all been cut through by Garryhorn Burn and sections are numerous. One in the westernmost large ridge (NX 522930) showed 3 m of very tough, stony, till that varied in colour from dark grey-brown (2.5Y, 4/2) to dark grey (5Y, 4/1). The matrix is clay-rich (over 18 per cent) and differs from that of the olive till of the Carsphairn Lane - Water of Deugh - River Ken valley where the mean clay content is 8.5 per cent. A pit excavated in the face of ridge 42 (NX 524930) showed a till very similar to that described above as did a section (NX 526931) in the third large ridge (43, Figure 7.2), the only differences between them being the colour, which was olive-grey (5Y, 4/2) and the clay content, which exceeds 20 per cent.

Between ridges 42 and 43 a small oval-shaped mound 100 m long is contiguous with the eastern flanks of ridge 42 (44, Figure 7.2). A riverbank section (NX 525929) in this feature showed 3 m of till whose colour (light olive-brown, 2.5Y, 5/4) was quite distinct from any other till seen in the Garryhorn Valley. The till was friable,

very stony and the matrix was sand-rich (57 per cent), but with the clay-size fraction well represented (15 per cent). No stratified deposits were found despite an extensive search. The fairly high clay content differentiates it from the normal olive till of the Carsphairn Lane - Water of Deugh - River Ken valley, but its colour is difficult to interpret.

East of ridge 43 the valley floor is flat and featureless over a distance of 300 m owing to sand and gravel deposits (45, Figure 7.2). The rather localised and small-scale nature of these deposits suggests they are outwash related to the Loch Lomond Advance glacier limits farther west. At the eastern termination of the outwash, by the defunct Woodhead lead and silver mines (Figure 7.2), till with a different morphological expression from that described above occupies the centre and sides of the valley. Instead of a cross-valley ridge form, a massive, amorphous valley-fill morphology is present (Plate XII). These deposits literally choke the Garryhorn valley for 1.3 km (46, Figure 7.2). They are best developed below 260 m O.D. and are thickest at the valley axis, where at least 11.5 m of till are exposed. No bedrock was seen to crop out at these locations. On the northern side of the valley the till grades into a thin drift cover that masks Garryhorn Rig (334 m). To the south, the deposits terminate at a well-defined drift limit at ca. 300 m O.D. on the north-facing slopes of Craighit.

Where Garryhorn Burn has partly dissected the valley-fill sections up to 4 m high (NX 532932; NX 534932; NX 534933) revealed a slightly indurated, clay-rich till, although in places it was quite sandy (see Chapter 8 for further discussion). All sections examined



Plate XII: Valley-fill deposits in the Garryhorn valley
(46, Figure 7.2).



Plate XIII: Deposits relating to Loch Lomond Advance glacier 1
(Figure 13.2) by Benyellary.

showed the till to be uniformly olive-grey (5Y, 5/2).

East of National Grid easting NX 542 the morphological expression of the till changes yet again, the valley-fill merging into small till ridges that are much less massive than those described farther west. They are normally 3 - 5 m high, less than 60 m wide and vary considerably in shape, some being elliptical in plan, some "beaded" (47, Figure 7.2) and some elongated (48, Figure 7.2). Few ridges display the same cross-valley trend as ridge 48. Many show a rather random orientation, while others are streamlined and possess drum-linoidal characteristics (e.g. ridges marked 49, Figure 7.2). Exposures in the ridges are uncommon. One small section in a ridge by Garryhorn Farm (NX 546933) revealed an indurated, clay-rich (20 per cent), olive-grey (5Y, 5/3) till, containing numerous angular clasts of greywacke. Contrastingly, an excellent exposure 150 m long by the Water of Deugh (NX 553932) exhibited 3 m of till whose colour varied between olive-grey (5Y, 4/2) and olive-brown (2.5Y, 4/4). The matrix, dominated by silt-size particles (57 per cent), was very tough and contained many boulders of greywacke up to 0.7 m long.

The till landform assemblage in the Garryhorn Valley is an important one, for it not only provides certain clues to the relationship between the cross-valley ridges and valley-fill deposits but also clues to the sequence of their formation and environment of deposition.

The first important feature is the absence of olive till (except at one locality) from the Garryhorn Valley. The predominance of grey till and the absence of either granite outcrops or erratics (except those at ca. 560 m O.D. on the summits of the Kells range: see Chapter 5) emphasises the importance of local bedrock geology on the

texture and colour of the till (cf. Drake 1971; Linden 1975; Haldorsen 1977; Perttunen 1977). Since the bedrock of the valley comprises greywackes, conglomerates and shales (Figure 2.2), it seems likely that these are responsible for the characteristic clay-rich nature and grey colour of the till found there.

The second interesting observation is that the grey till forms cross-valley ridges, that are of both large and small size, and valley-fill. This indicates that the ridge-forming process operated on both the grey and olive (sections (ii) and (iv)) tills, which implies that the two were deposited in a similar environment. A similar inference may be made about the valley-fill deposits, which are also composed of olive and grey till (sections (iii) and (v)). Moreover, this relationship suggests that the two tills are of similar age (viz: Late-Devensian).

The valley-fill/cross-valley ridge relationship recorded from the western part of the Garryhorn Valley is similar to that found in the River Ken valley by Marscalloch Hill and in the Water of Daugh valley by Knockgray Farm. These relationships imply a genetic link between both of the tills (olive and grey) and both of the landforms (cross-valley ridges and valley-fill) and therefore suggest that the control of landform type created was largely a function of ice condition and local relief.

The third main aspect is the large quantity of till in such a small valley. This is in marked contrast to the three other tributary valleys to the south (Polmaddy, Polharrow, Garroch). It is suggested that this difference relates to flow conditions in the Late-Devensian ice-sheet in this area. Two aspects are important here.

- 1) It has been argued in Chapter 5 that blockage of ice flow at the Garryhorn - Water of Deugh valley confluence, by the meeting of valley glaciers (emanating from the tributary valleys on both sides of the main Carsphairn Lane - Water of Deugh valley) during initial ice-sheet growth, produced an environment of ice stagnation that restricted the evacuation of debris from the area at an early stage.
- 2) Erratics (Chapter 5) show that an ice-shed existed in the area immediately south of Garryhorn Valley during the Late-Devensian maximum. This also would have limited the transport of debris from the Garryhorn Valley owing to negligible horizontal ice movement.

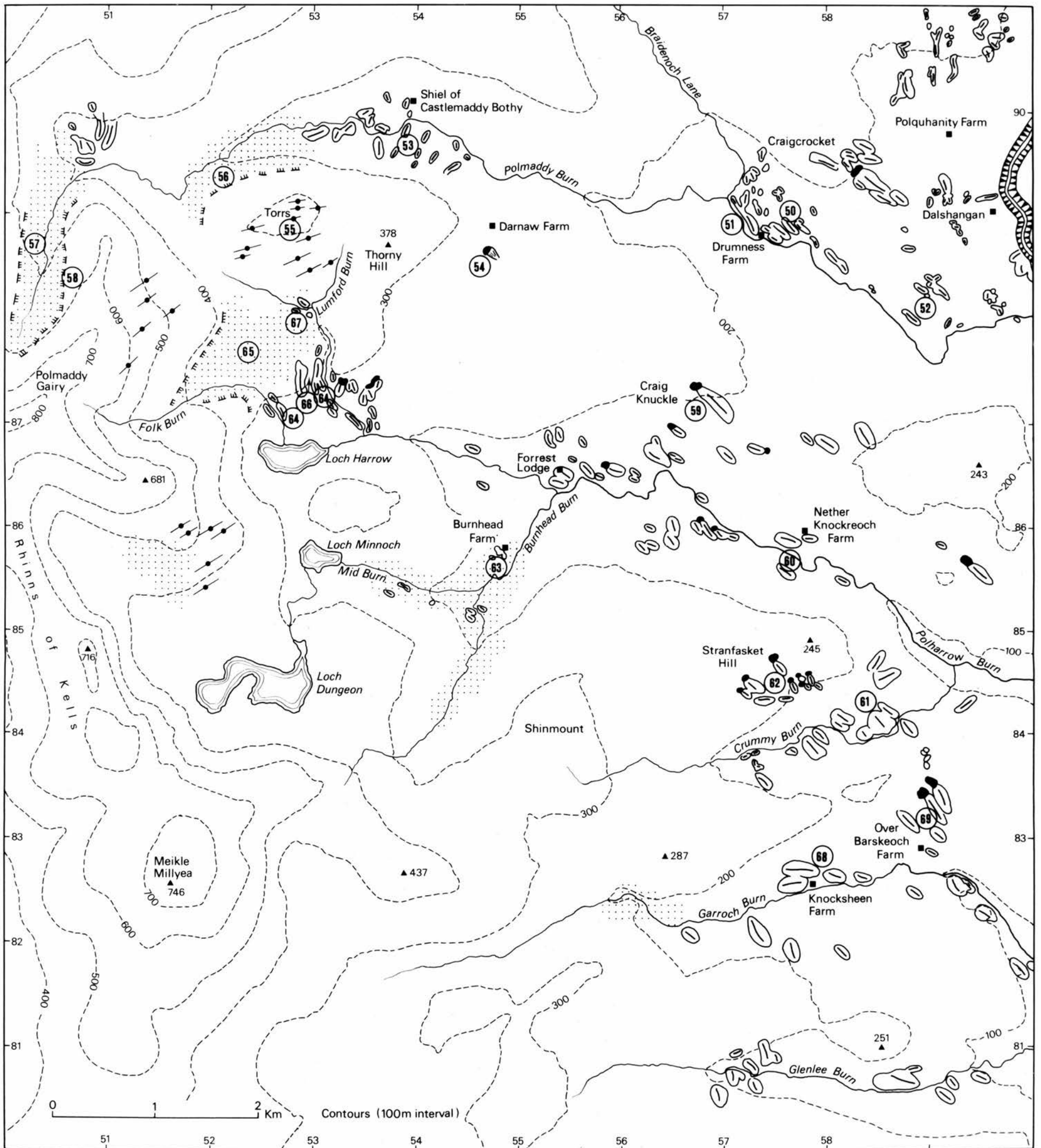
Thus ideal conditions for the accumulation of large volumes of almost stagnant, debris-rich ice pertained in this area during both the early and maximum stages of ice-sheet development. This debris would thus have been available at a later stage for the formation of the till landform assemblage found in the Garryhorn Valley. These inferences also have important implications for cross-valley ridge formation in the main Carsphairn Lane - Water of Deugh - River Ken valley and will be discussed in Chapter 12. The more limited occurrence of till deposits in the tributary valleys farther south may be explained by ice flow being less restricted by the ice-shed and free to move along the NW-SE valleys, preventing large quantities of debris accumulating. The presence of drumlinoid landforms in these valleys accords with this view.

(viii) The Polmaddy, Polharrow and Garroch Valleys and their interfluve areas.

This area is dominated by generally NW-SE valleys whose heads are cut into the eastern flanks of the Rhinns of Kells range (Figure 7.13). All the valleys show evidence of extensive erosion by ice, particularly in their SE sections where they merge with the main Carsphairn Lane - Water of Deugh - River Ken valley. The interfluve areas exhibit more extreme forms of ice-scouring and the drift cover is normally very thin in these locations.

Deposits of till are present, however, and are well developed in the 3 km section of the Polmaddy Burn valley SE of its confluence with Braidenoch Lane (Figure 7.13). By the confluence of the two streams the till forms oval hummocks 5 - 7 m high, while to the SE several of the ridges are more elongated (50, Figure 7.13). The latter are aligned NW-SE and parallel the trend of the valley. Other ridges in the same area are orientated in the same direction but are much longer and narrower, possessing an esker-like morphology. A particularly good example is located NW of Drumness Farm (51, Figure 7.13). This feature is 500 m long, 12 - 15 m high and bifurcates at its NW end. Peat-filled dead-ice hollows are present on the NE side of the main ridge, but the SW flanks have been trimmed by the Polmaddy Burn, to which the ridge no doubt owes part of its morphological expression. Poorly exposed sections in this side of the ridge showed an indurated olive-grey (5Y, 5/2) till. Better sections in the drumlinoid ridges to the SE (e.g. NX 579887; NX 576888) revealed a very tough, silt/sand-rich, olive-grey till below a reddish-yellow oxidised horizon 0.5 m thick. Clasts and boulders of angular greywacke up to 0.6 m long

Figure 7.13 Glacial landforms in the Polmaddy, Polharrow,
Garroch and Glenlee valleys. Key as for
Figure 7.3.



were common.

Farther SE (52, Figure 7.13) the till forms only a relatively thin cover over the bedrock. Small hummocks are present (e.g. NX 591875) composed of the same kind of till as mentioned above. Numerous bedrock knolls, however, suggest a large degree of bedrock control over the morphology of these forms. NW-SE ice movement in this section of the valley is recorded by the drumlinoid forms by Craigcrocket (described in section (iv)).

A second group of till landforms occurs 3 km WNW of ridges 50 and 51 by Shiel of Castlemaddy bothy (53, Figure 7.13), where low (2 - 5 m high), irregularly spaced ridges up to 150 m long appear to trend across the valley. The ridges are "beaded", which gives them an undulating crest-line. They merge into the till blanket that covers the lower slopes of Thorny Hill above 270 m O.D. Their composition is displayed in riverbank sections (e.g. NX 530898; NX 536898) and by a forestry road (e.g. NX 540896; NX 542895; NX 543895). In one riverbank section 5 m of tough, sand-rich, olive (5Y, 5/3) till was exposed, while all the roadside sections showed 1 - 2 m of till resting directly on ice-moulded bedrock. Bedrock knolls protrude through the crest-lines of the ridges in places. Striae indicate NW-SE ice flow, as does the crag-and-tail (54, Figure 7.13) by Darnaw Farm and elongated ice-moulded bedrock ridges forming the summit of Torrs Hill (55, Figure 7.13). The extensive exposures of bedrock in the vicinity of the ridges suggest that the cross-valley trend of these "ridges" is due to bedrock control.

Farther upstream (to the west) the till forms a featureless blanket with a valley-fill morphology. It covers the northern slopes

of Torrs Hill below 360 m O.D. (56, Figure 7.13). Bluffs by the Polmaddy Burn showed up to 6 m of tough, silt-rich, olive-grey till containing numerous cobbles and boulders of greywackes. Similar deposits occupy the S-N-trending U-shaped trough in the upper reaches of Polmaddy Burn (57, Figure 7.13) below Polmaddy Gairy. At one location (NX 504889) in this area 8 m of till rests directly on bedrock exposed in the stream bed. The till is largely confined to the valley axis and thins rapidly against both valley sides at a drift limit that rises from 450 m O.D. at the northern end of the trough to 580 m O.D. at its head (58, Figure 7.13).

The interfluvial area between the Polmaddy and Polharrow valleys has extensive areas of blanket peat and ice-scoured bedrock. Till on the south-facing slopes of the interfluvial forms drumlinoids, which are normally orientated NW-SE. Many of these features are bedrock controlled, exemplified by the two located by Craig Knuckle (59, Figure 7.13). The stoss end of both forms comprise a bedrock knoll partly smoothed by ice, to the SE of which a drift "tail" has been deposited.

Till deposits with a drumlinoid morphology occupy the floor and sides of Polharrow Valley (Figure 7.13). They parallel the valley trend as well as the direction of former ice movement as demonstrated by striae in the valley (Figure 5.7). The drumlinoids are rather poorly developed, comprising low, generally flat-topped mounds 4 - 10 m high and less than 250 m long. Many show evidence of bedrock control but one section (NX 576856) in a drumlinoid by Nether Knockreoch Farm (60, Figure 7.13) showed 5 m of indurated, olive (5Y, 5/3) till with a silt/sand-rich matrix.

Similar landforms occur in the adjacent Crummy Burn valley (61, Figure 7.13), but as the valley trend is perpendicular to the direction of former ice movement the drumlinoids are plastered across the valley. These again are low features (4 - 5 m high) and several are bedrock controlled, especially those located on the south-facing slopes of Stranfasket Hill (62, Figure 7.13). Roadside sections (e.g. NX 587846; NX 587841; NX 594843) all showed a very tough, silt-rich, olive till.

West of Forrest Lodge in the Polharrow Valley the drumlinoids are accompanied by patchy valley-fill deposits into which Polharrow and Burnhead Burns are incised. In the latter valley, by Burnhead Farm (63, Figure 7.13), a river-cut section (NX 549856) 9 m high showed an upper weathered horizon (0.6 m thick) merging into a hard, silt-rich, olive till containing cobbles of both greywacke and granite (derived from the Burnhead satellite granite intrusion). Small, randomly orientated till hummocks rise 2 to 3 m above the general surface of the valley-fill in the same area. Bedrock knolls protruding through the drift near the valley axis suggest that the cover is thin.

The drumlinoids of the upper reaches of Polharrow Valley are almost entirely bedrock controlled. They merge into a group of mounds and elongated ridges NE of Loch Harrow (64, Figure 7.13). The ridges are 3 - 10 m high, up to 300 m long and appear to be orientated N-S, parallel to Lumford Burn. Numerous sections (e.g. NX 535869; NX 534870; NX 531874) showed a fairly indurated, sand-rich olive till containing numerous boulders of greywacke and occasional cobbles of porphyrite. The landforms merge westwards into

till with a valley-fill morphology (65, Figure 7.13) that occupies the valley of Folk Burn below a drift limit at ca. 400 m.

Many of the ridges appear to owe their morphology partly to fluvial action, which has exaggerated their elongated nature. For example, a meltwater channel (66, Figure 7.13) is locally responsible for the N-S trend. Similarly by the confluence of Lumford and Polharrow Burns (NX 535869), the ridges closely follow the meandering stream course, which again suggests control by fluvial incision. More extreme examples occur by 67 in Figure 7.13 where valley-fill has been dissected by closely spaced streams to produce a secondary ridge morphology. In addition bedrock crops out extensively in the beds of Lumford and Folk Burns as well as in the flanks of some of the ridges, indicating a degree of bedrock control on ridge morphology.

Some of the mounds, however, seem to be constructional, especially those east of Lumford Burn, where streamlined drift tails leading south from ice-moulded bedrock knolls imply ice movement in this direction. No confirmatory evidence such as striae was found.

These landforms were described by Charlesworth (1926a), who suggested that they were related to his "Corrie Moraine" stage. The present observations, however, indicate that the till was deposited from the Late-Devensian ice-sheet and that most of the ridges were controlled by bedrock outcrops or have resulted from fluvial dissection of the till sheet.

Landform mapping on the interfluvium between the Polharrow and Garroch Burn valleys was impracticable owing to extensive plantations of 30 year old conifers. However, this did not apply to the

interfluvium between the Crummy Burn and Garroch valleys or to the valleys occupied by the Garroch and Glenlee Burns. The landforms in the latter two valleys show a similar sequence to those described from the Polharrow and Polmaddy valleys farther north. Till with a valley-fill morphology, which fades rapidly away from the valley axes, is sporadically developed in the more western parts of both valleys (Figure 7.13). It gives way eastwards to drumlinoid landforms, some with bedrock cores, that occupy the valley floor and sides. Although these features and striae (Figure 5.7) indicate that former regional ice flow was NW-SE, there are certain anomalies. For example, the drumlinoids located by Knocksheen Farm (68, Figure 7.13) trend W-E, parallel to the orientation of the valley. Sections in these landforms (e.g. NX 577825) showed a tough, sand-rich, olive till and seem to indicate that the drumlinoids are entirely composed of drift. Immediately to the east, however, by Over Barskeoch Farm (69, Figure 7.13) rock-controlled drumlinoids trending NW-SE again parallel valley alignment. These observations suggest that relief was an important controlling feature with respect to ice flow and conditions of till deposition.

As mentioned in section (vii) the glacial landforms in these valleys indicate deposition from active ice. The drumlinoids and striae indicate a NW-SE regional ice movement. The drumlinoids are confined to the more easterly sections of the valleys and are preferentially located on the valley floors and sides. These observations suggest a powerful ice flow from the eastern flanks of the Rhinns of Kells range, its direction being generally oblique to the valley trends. The increase in bed roughness provided by the valleys would

have created ideal conditions for till deposition owing to the increased effective pressure at the glacier bed. On the other hand, the somewhat limited extent of glacial deposits as well as the distance from the former ice-shed zone farther north suggests that ice flow in this area was relatively rapid and did not favour the build-up of large amounts of debris; drumlinoids were therefore deposited.

7.3 SUMMARY AND CONCLUSIONS

The depositional landforms associated with the Late-Devensian ice-sheet described and discussed in this chapter are dominantly composed of till: those of sand and gravel are of restricted extent, being confined to the NW parts of the Carsphairn Lane valley.

Two tills are exposed in the area. A grey basal unit with a clay-rich matrix is succeeded by a till that is normally olive in colour and characterised by a sand- or silt-rich matrix that is usually indurated. In all exposures examined where both tills were present the olive till overlay the grey till. The contact between the two tills was always sharp, and at one location the contact was complicated by deformation that had produced load structures.

Till landforms include amorphous deposits with a valley-fill morphology, drumlinoids and drumlins. The most unusual landforms recorded, however, are what will be termed "cross-valley ridges". These attain their best development in the Water of Deugh valley between Craig of Knockgray and Dundelugh Hill. The ridges in this area were composed only of olive till in all the sections examined. They possess several features of interest, the most important being as follows.

- 1) General orientation ^{is} perpendicular to the direction of former regional ice movement.
- 2) They are absent above 275 m O.D.
- 3) The ridges do not continue on the opposite side of the valley. Only two, larger, ridges possess such a continuity, one of these showing a morphological relationship to the adjacent valley-fill deposits by Craig of Knockgray.
- 4) The upper surfaces of the larger ridges are drumlinised. The ridges in the SE part of the area containing them also display a drumlinoidal form.
- 5) The ridges merge into drumlinoids and crag-and-tail forms down-ice as well as on some adjacent valley sides above 275 m O.D.

All the above-mentioned landforms in the main Carsphairn Lane - Water of Deugh - River Ken through-valley bear a close morphological relationship with one another, which implies that the relationship is a genetic one. In this valley, in a down-ice direction, valley-fill deposits merge into cross-valley ridges that in turn give way to drumlinoids and drumlins.

Both olive and grey tills have been observed to comprise each type of landform mentioned above, while the olive till examined in the cross-valley ridges of the Water of Deugh valley is very similar to that observed in the drumlinoids and valley-fill deposits. These observations suggest that both tills were deposited in the same glacial environment. This, plus the close association of the cross-valley ridges with the drumlinoids and drumlins implies a subglacial position for the deposition of the tills.

Related to these aspects is the disposition and amount of till present in what was an ice-shed zone and where horizontal ice movement would have been very limited. As a generalisation, it seems that conditions of deposition from the ice in the Water of Deugh valley between Craig of Knockgray and Dundough Hill, where movement was parallel to the valley axis, promoted the formation of cross-valley ridges while in the adjacent valleys where the ice tended to flow across or oblique to the valley trend, a valley-fill morphology is the norm. Further, it has been argued in Chapter 5 that basal ice stagnation in the area promoted the early build-up of large volumes of debris-rich ice. Evacuation of this debris would have continued to have been restricted not only because of the development of an ice-shed in this area during the Late-Devensian maximum but also because of the influence of local relief, in particular the large mass of Dundough Hill.

Evidence for the more rapid movement of ice at locations farther removed from the ice-shed (and where local relief was less restrictive) is provided by:

- 1) drumlinoids such as those by Craigcrocket hill and those in the River Ken valley, above its confluence with the Water of Deugh, and Polmaddy, Polharrow and Garroch valleys.
- 2) the absence of cross-valley ridges south of Dundough Hill. Here, ice velocity would have been increased, not only by the steeper valley gradient, but also by the addition of large volumes of ice from glaciers nourished on the eastern flanks of the Kells range.

Meltwater channels have been described from the area in association with fluvioglacial deposits as well as with valley-fill and cross-valley ridge landforms. As the channels have been shown to cut the two latter types of landform, formation of the valley-fill and cross-valley ridges prior to the final phase of ice-sheet wastage is implied.

The restricted occurrence of fluvioglacial deposits is explained by meltwater flow from the wasting ice-sheet being impeded only at the NW end of the Carsphairn Lane valley by the watershed. This caused an englacial water-table to develop in the ice, with meltwater escaping along three large channels, thus controlling the deposition of fluvioglacial sands and gravels. During the later stages of ice decay normal drainage towards the SE was re-established. The absence of fluvioglacial landforms from the area SE of the former ice-shed zone is interpreted as being due to flow of meltwater along the valley lines occupied by the present drainage system.

CHAPTER EIGHT
 PARTICLE-SIZE ANALYSIS OF TILLS FROM
 THE CARSPHAIRN LANE - WATER OF DEUGH -
 RIVER KEN AREA

8.1 INTRODUCTION

The particle-size characteristics of the matrix (i.e. < 2 mm diameter) of 61 till samples from various exposures in the Carsphairn Lane - Water of Deugh - River Ken valley were determined; the analytical procedures have already been outlined in Chapter 3. The particle-size analyses were undertaken to test for any differences between the grey and olive tills and in turn to relate these to the particle-size characteristics of the cross-valley ridge, valley-fill and drumlin landforms in the Carsphairn area. Further, it was hoped to draw inferences from the results regarding composition, mode of glacial transport and deposition of the tills that comprise the above-mentioned landforms. The three additional samples from till deposits located on the Loch Doon granite pluton have been considered in Chapter 6 and are therefore not included here. The tills were sub-divided in the following manner for analysis:

- 1) Olive till (n = 48): within this generalised category are ten samples from valley-fill (8) or inter-ridge till deposits (2) adjacent to the cross-valley ridges, 29 from the cross-valley ridges, five from drumlinoids and four from drumlins.
- 2) Grey till (n = 13): comprising five samples from valley-fill deposits in the River Ken valley: two from the basal parts of

a cross-valley ridge in the Carsphairn Lane valley, five from the Garryhorn Valley (one from the base of a cross-valley ridge, two from valley-fill and two from large cross-valley ridges) and one from a valley-fill deposit in the Water of Deugh valley.

The exact location of the sample sites is tabulated in Appendix I.

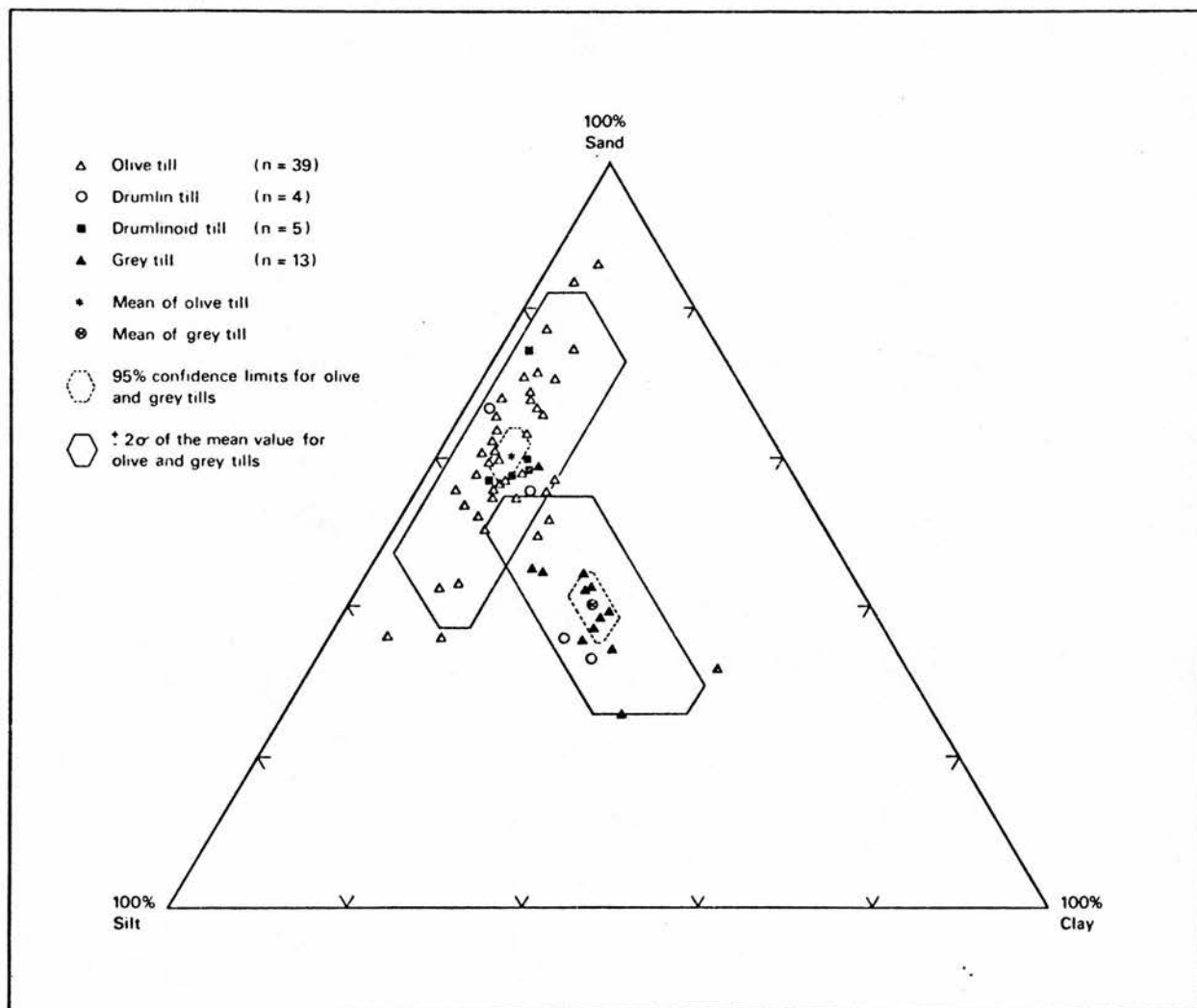
8.2 RESULTS AND ANALYSIS

The results of the particle-size analysis of all the till samples are shown on the ternary diagram in Figure 8.1. Summary statistics for the particle-size composition of the tills are presented in Table 8.1 (see Appendix I for detailed results). It is apparent from Figure 8.1 that a clear differentiation exists between the olive and grey tills. Even when the $\pm 2\sigma$ field is plotted around the grand mean particle-size for each till (excluding the drumlin and drumlinoid samples) there is very little overlap.

The olive till samples display a broad particle-size distribution. This is due to the large variability in the percentage sand ($V\% = 18.4$) and silt ($V\% = 30.9$) content, the range being 35% - 85% and 8% - 57% respectively. The olive till is characterised by a low clay content, ranging from 4% - 17% ($V\% = 41.2$). All except four samples lie within $\pm 2\sigma$ of the grand mean; the mean particle-size composition of the olive till samples (excluding the drumlin and drumlinoid samples) is 60% sand, 31.5% silt and 8.5% clay. Subdividing the olive till samples further, analysis of those from the cross-valley ridges alone shows their mean particle-size to be 61.1% sand, 30.5% silt and 8.4% clay. Olive till samples from valley-fill

Figure 6.1

**Ternary diagram of the results of the particle-size
analysis of the matrix of tills from the
Carsphairn Lane - Water of Deugh - River Ken area.**



deposits are almost identical, their mean composition being 62% sand, 29.5% silt and 8.5% clay. These results confirm the observations made in Chapter 7 regarding the close morphological affinities between the valley-fill and cross-valley ridges.

The major component differentiating the grey till from the olive is the former's clay content, which in all samples except one lies between 18% and 46% ($V\% = 31.1$). The single anomalous sample (12% clay and a correspondingly higher sand percentage) comes from the valley-fill deposits that occupy the central part of the Garryhorn Valley (NX 532932; 46, Figure 7.2). The result is curious in that a second sample from the same till mass (NX 534932) yields nearly 30% clay. As the samples were carefully checked for particle aggregation during analysis, it seems likely that the sample was excavated from a particularly sand-rich lens in the till, although no visible signs of such were observable. The silt content of the grey till ranges from 21% to 36% ($V\% = 12.2$) and is generally comparable with the silt-size particle percentages in the olive till. The percentage of sand-size particles, however, is normally less than in the olive till ranging from 25% to 45%, except for the 58% recorded for the atypical sample described above. All except one of the grey till samples fall within the $\pm 2\sigma$ field and six occur within the 95% confidence limits (Figure 8.1). The mean particle-size composition of the grey till is 40% sand, 31.9% silt and 28% clay.

The samples from the drumlinoid and drumlin landforms show an interesting separation within themselves and are plotted as a different ornament in Figure 8.1. The two samples from drumlins that fall within the $\pm 2\sigma$ range of the grey till were excavated from "text-book"

Table 8.1 Summary statistics for the particle-size composition
of the matrix of tills sampled from the Carsphairn Lane -
Water of Deugh - River Ken area.

		SAND	SILT	CLAY
olive till (n = 29)	\bar{x}	61.1%	30.5%	8.4%
	σ	10.15	8.58	3.63
(cross-valley ridges)	V%	16.6	28.1	42.9
olive till (n = 8)	\bar{x}	62.0%	29.5%	8.5%
	σ	9.02	7.85	3.4
(valley-fill)	V%	14.5	26.6	40.0
olive till (n = 2)	\bar{x}	36.0%	54.25%	9.75%
	σ	0.35	4.03	4.45
(inter-ridge till)	V%	0.97	7.4	45.6
olive till (n = 4)	\bar{x}	47.9%	33.6%	18.5%
	σ	15.9	3.3	12.9
(drumlins)	V%	33.2	9.8	69.7
olive till (n = 5)	\bar{x}	61.2%	30.2%	8.5%
	σ	7.5	4.9	3.2
(drumlinoids)	V%	12.2	16.2	37.6
grey till (n = 13)	\bar{x}	40.0%	31.9%	28.0%
	σ	7.9	3.9	8.7
	V%	19.75	12.2	31.1

\bar{x} = mean

σ = standard deviation

V% = coefficient of variation

drumlins situated well outside the down-valley terminations of the cross-valley ridges. One sample is from a drumlin by Balmaclellan (NX 651787), which lies in the NW part of the Galloway drumlin field (17 km SE of the former ice-shed zone by Carsphairn, see Chapter 5) and the other is from a drumlin located by Loch Doon (NX 498998), 8 km NW of the former ice-shed. The mean particle-size for the two samples is 35% sand, 36% silt and 29% clay. The other two samples from drumlins fall within the $\pm 2\sigma$ field of the olive till. These landforms, however, comprise muted drumlin forms and bear a close morphological affinity to the drumlinoid landforms (mentioned above) in their immediate vicinity. This relationship is borne out by their particle-size properties, which are almost identical (Figure 8.1). Further, these landforms occur immediately outside the down-valley limits of the cross-valley ridges. The mean particle-size composition for the two muted drumlin forms, the five drumlinoids, 29 samples from the cross-valley ridges and eight from the valley-fill deposits is as follows:-

		% sand	% silt	% clay
muted drumlins	(n = 2)	61.0	31.0	8.0
drumlinoids	(n = 5)	61.2	30.2	8.5
cross-valley ridges	(n = 29)	61.1	30.5	8.4
valley-fill	(n = 8)	62.0	29.5	8.5

A clear similarity is obvious. Although some of the sample sizes are too small to permit any statistical inference, the close affinities both in terms of particle-size and landform association (Chapter 7) is important and will be discussed in Section 8.3.

The particle-size data were also plotted as cumulative frequency distributions on probability paper (Hatch and Choate 1929). The dependent variable is frequency expressed as a cumulative percentage finer by weight, while the independent variable is grain size with diameters expressed in phi (ϕ) units (Krumbein 1934). Use of a log conversion results in a more symmetrical particle-size distribution curve and the probability scale allows a visual estimation of the normality of the curve. With a normal distribution, the cumulative frequency should plot as a straight line and as such may be analysed by parametric statistical moment methods (Friedman 1961). This procedure was adopted against direct calculation of the particle-size parameters without graph plotting (cf. Kane and Hubert 1963; Koldijk 1968), for without visual inspection of the frequency curves bimodality in the data may not be detected and any genetic relationships overlooked. The envelopes enclosing the frequency distributions of the olive and grey tills are shown in Figure 8.2 (note the different curve for the atypical gray till sample described on p. 180), and the curves for the drumlin and drumlinoid samples in Figure 8.3.

In order to compare quantitatively the results obtained from the particle-size analysis the measures of mean size, coefficient of sorting and other frequency distribution parameters were calculated (Appendix I). These properties have been employed by numerous workers in attempts to differentiate various sediment types (including tills) as well as environments of deposition (e.g. Krumbein 1933; Folk and Ward 1957; Friedman 1961, 1962, 1967; Shephard and Young 1961; Folk and Robles 1964; Kelly and Baker 1966; Drake 1968; Landim and Frakes 1968; Vorren 1977; Mills 1977a). Approaches to the calculation of these distribution parameters differ in two basic ways, in that

Figure 8.2 Particle-size distribution envelopes for olive
and grey tills.

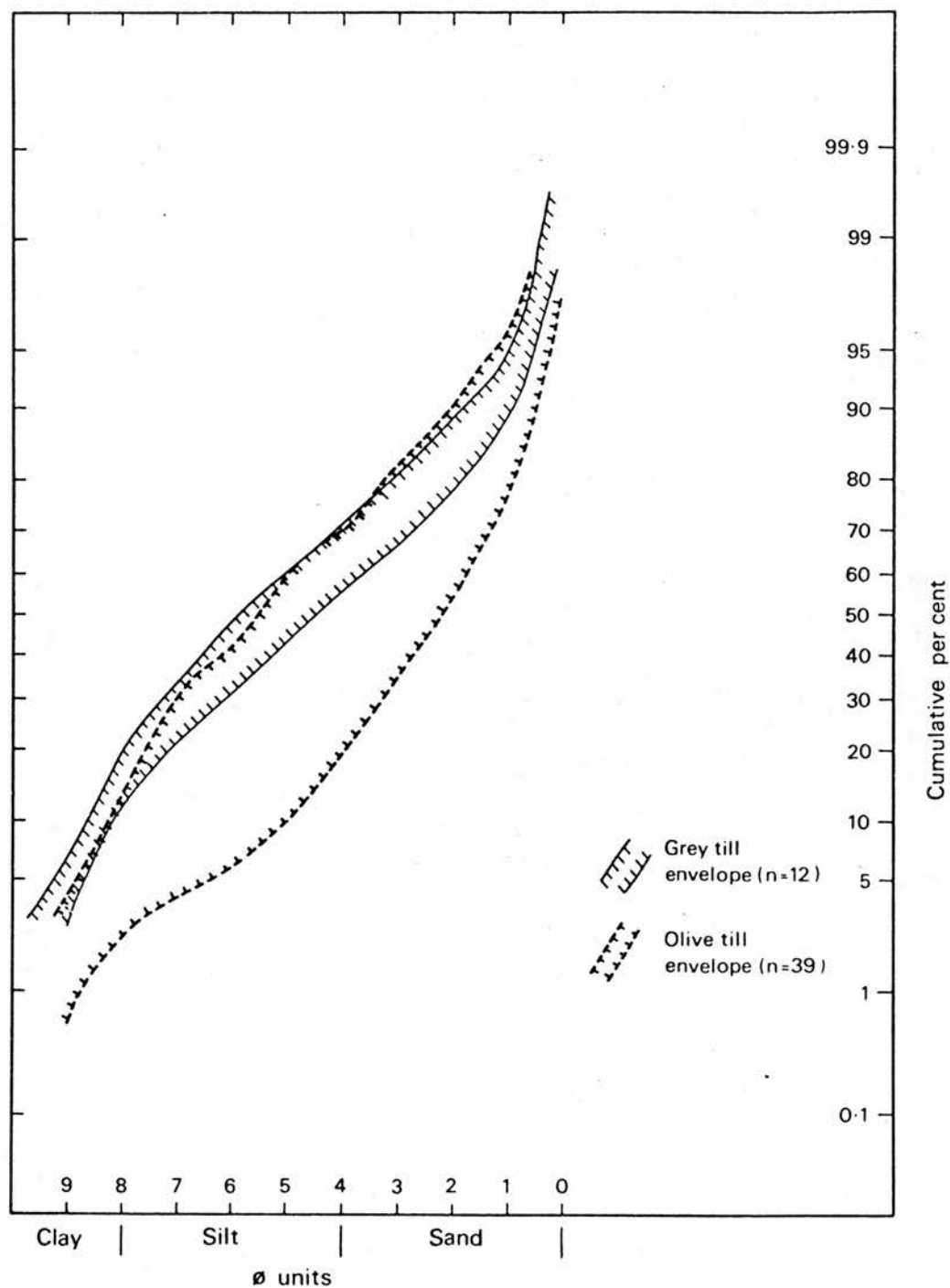
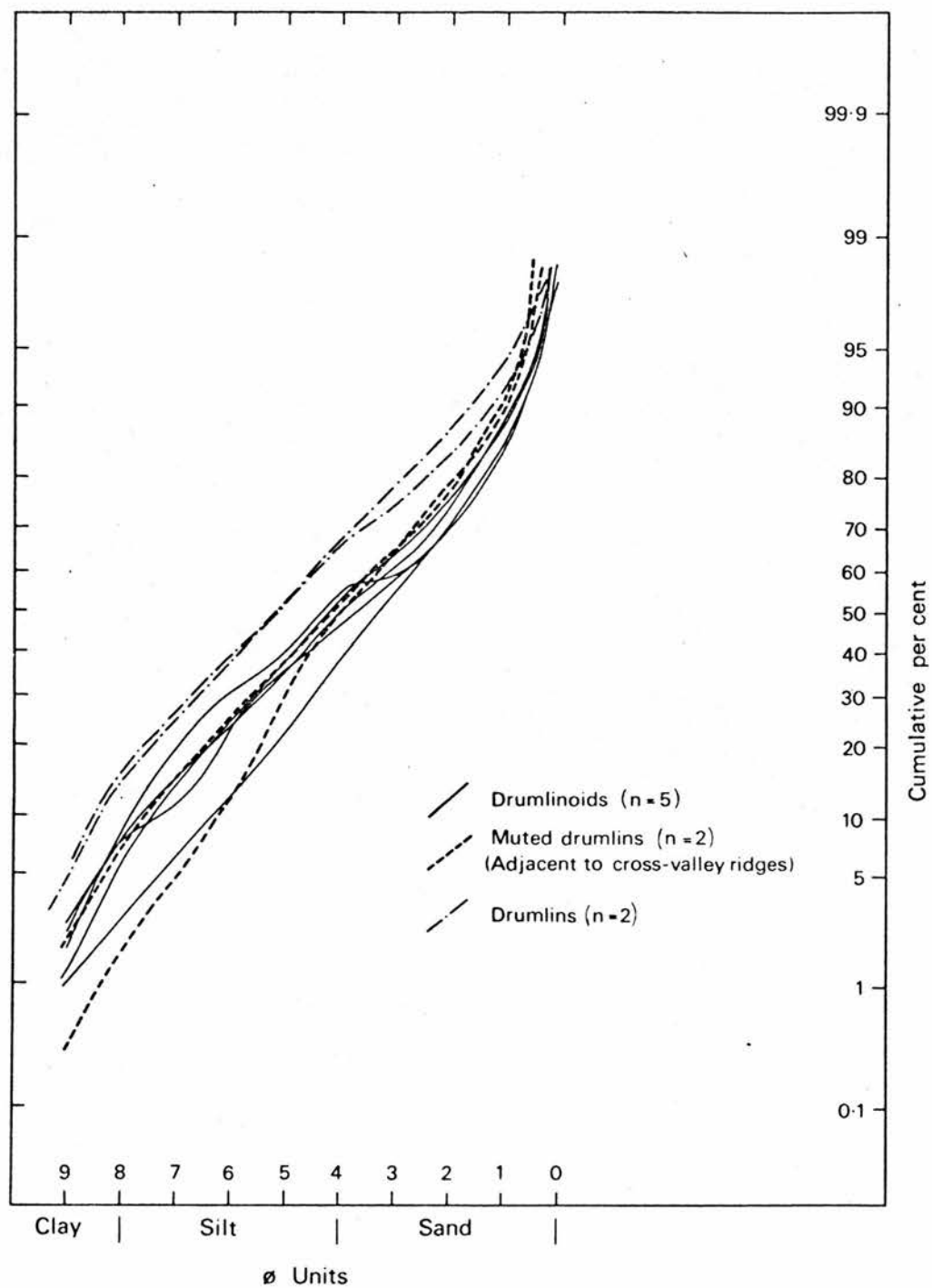


Figure 8.3 Cumulative curves for particle-size distributions of drumlin and drumlinoid tills.



either percentile measures (graphically calculated) or moment measures (frequency computations) have been employed. The merits and drawbacks of both procedures have been exhaustively reviewed by McCammon (1962), Folk (1966) and Swan *et al.* (1978) and need not be considered here. Although moment measures have been shown, in some cases, to be more sensitive indicators than graphic measures (Friedman 1962; Koldijk 1968), it is generally considered that the former should only be used on data that are unimodally distributed (Folk and Ward 1957; Folk 1966; Landim and Frakes 1968).

Frequency plots of the particle-size distributions determined for the tills in the Carsphairn area showed that 42 of the samples were bimodal, while 19 possessed multimodal characteristics. Thus the graphical procedures outlined in Folk and Ward (1957) and McCammon (1962) were used to calculate the Graphic Mean (M_z), the Inclusive Graphic Standard Deviation (σ_I), the Inclusive Graphic Skewness (Sk_I) and the Graphic Kurtosis (K_G) of all 61 samples analysed. Only those measures with the highest statistical efficiency were employed. The equations and statistical efficiency of the measures used in these calculations are presented in Table 8.2. McCammon's (1962) equation for Graphic Mean and Inclusive Graphic Standard Deviation were preferred to those of Folk and Ward (1957) as the number of percentiles taken into account in the calculations is larger, and thus gives a more accurate approximation to the M_z and σ_I results. As these modified equations are mutually independent, they can be applied to non-normal and bimodal distributions.

The graphic measures were calculated by reading off the percentile values from the cumulative curves drawn for each sample. All curve

Table 8.2 Equations and statistical efficiency of the measures
used in the calculation of the particle-size parameters.

Graphic Mean

$$M_z = \frac{(\phi 5 + \phi 15 + \phi 25 + \phi 35 + \phi 45 + \phi 55 + \phi 65 + \phi 75 + \phi 85 + \phi 95)}{10}$$

after McCammon (1962). Statistical Efficiency = 97%

Inclusive Graphic Standard Deviation

$$\sigma_I = \frac{(\phi 70 + \phi 80 + \phi 90 + \phi 97 - \phi 3 - \phi 10 - \phi 20 - \phi 30)}{9.1}$$

after McCammon (1962). Statistical Efficiency = 87%

Inclusive Graphic Skewness

$$Sk_I = \frac{\phi 16 + \phi 84 - 2\phi 50}{2(\phi 84 - \phi 16)} + \frac{\phi 5 + \phi 95 - 2\phi 50}{2(\phi 95 - \phi 5)}$$

after Folk and Ward (1957).

Graphic Kurtosis

$$K_G = \frac{\phi 95 - \phi 5}{2.44(\phi 75 - \phi 25)}$$

after Folk and Ward (1957).

parameters were read to the nearest 0.01ϕ , an accuracy that is meaningful when cumulative percentage frequency curves are plotted on probability paper (Folk 1955). The results of these calculations are tabulated in Appendix I, the overall variations in Figure 8.4 and the grouped particle-size parameter values in Table 8.3. The results of the analysis of the four particle-size distribution parameters calculated are considered below.

Figure 8.4 Histograms of the distribution of particle-size
parameter values for olive and grey tills.

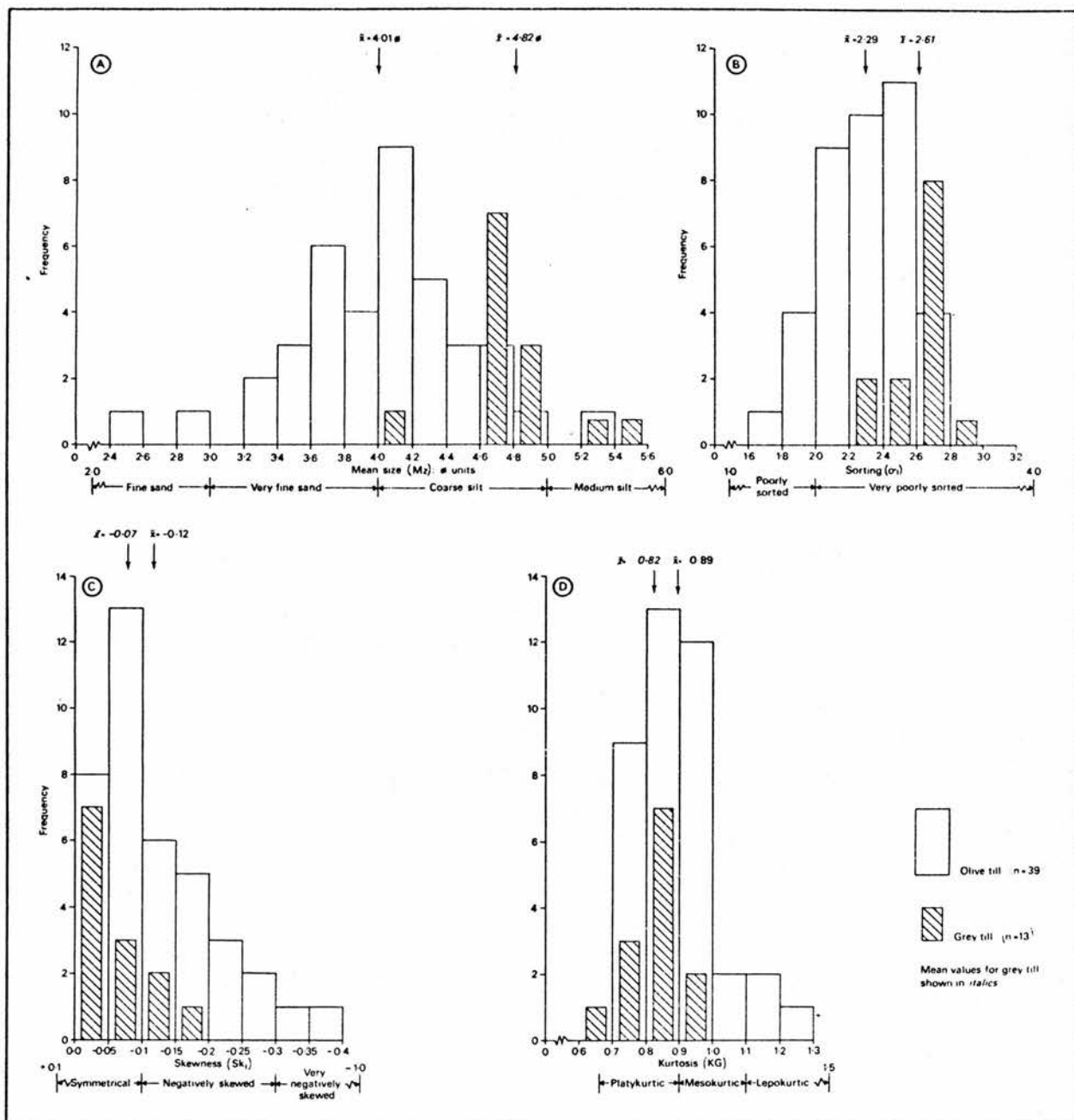


Table 8.3 Values of maximum (x_{max}) and minimum (x_{min}) and mean (\bar{x}) ± 2 standard errors of the particle-size parameters for the grey and olive tills (excluding drumlin and drumlinoid samples) from the Carsphairn Lane - Water of Deugh - River Ken area. n denotes the number of samples.

Parameter	x_{max}	x_{min}	\bar{x}	± 2 S.E.	n	Till type
M_z	5.26 ϕ	2.94 ϕ	4.01 ϕ	0.17	39	olive
M_z	5.52 ϕ	4.02 ϕ	4.82 ϕ	0.18	13	grey
σ_I	2.79	1.76	2.29	0.08	39	olive
σ_I	2.82	2.39	2.61	0.07	13	grey
Sk_I	-0.37	-0.01	-0.12	0.03	39	olive
Sk_I	-0.19	-0.01	-0.07	0.03	13	grey
K_G	1.29	0.72	0.89	0.04	39	olive
K_G	0.99	0.68	0.82	0.04	13	grey

(i) Graphic Mean (M_z)

This measure reflects the overall average size of the till matrix as influenced by factors such as source of supply, mode of transport, environment of deposition and post-depositional changes. Folk (1966) has stated that there are three dominant modal populations in natural sediments: (1) gravel, (2) sand, (3) coarse silt and clay. These result, he suggested, from breakage along joints or bedding-planes, granular disintegration and from chemical decay respectively. Wentworth (1933) and Pettijohn (1957) also observed this phenomenon, showing that two strong voids occur in sediment distributions; one

at -1ϕ and one at 8ϕ , with a weaker gap at 3.5ϕ . Griffiths (1967) challenged these conclusions, suggesting that the gaps were merely a function of the change in analytical procedures; viz. direct measurement, screens and pipette. All the above observations, however, have been made with regard to sediments other than till. The uniqueness of the glacial environment in producing characteristic particle-size distributions has been emphasised by Dreimanis and Vagners (1969, 1971), Beaumont (1971b) and Boulton (1978). Beaumont (1971b) found consistent breaks in particle-size curves of till at 2.2ϕ to 0.2ϕ , which he attributed to a change in the nature of the till from a dominance of rock fragments to one of mineral grains. Boulton (1978) specifically criticized Griffiths' (1967) observations, stating that the voids did not occur where analytical procedures changed, but represented zones of depletion where sediment was under-represented owing to differences in the nature of debris transportation in glaciers; the particle-size distribution of tractional debris was usually enriched in the fine fraction (fine sand/silt range) and depleted in the coarse fraction. These results have an important bearing on this study and are discussed in detail in Section 8.3.

The variations in the values for the mean size (ϕ units) of both the olive and grey tills are shown in Figure 8.4A. A clear difference between the two types is observable, and this is reflected in the grand mean values of 4.0ϕ for the olive and 4.82ϕ for the grey. It is interesting to note here that in both the olive and grey tills the mean M_z values fall within the silt-size grade (4.0 to 5.0ϕ). The M_z values for both olive and grey tills have been compared using

the Mann-Whitney U-test against the null hypothesis that both tills are drawn from the same population. The results show that the null hypothesis is rejected at the 0.01 level ($p = 0.001$ in the U-Tables; Dixon and Massey 1969), indicating that the two tills are significantly different in terms of their mean size and may be said to come from different populations.

(ii) Inclusive Graphic Standard Deviation (σ_I).

This measure is an indicator of the sorting properties of any sediment; values between 1.0 and 2.0 indicate poor sorting, while those between 2.0 and 3.0 indicate very poor sorting (Folk and Ward 1957). The mean sorting value for all the olive till samples ($n = 39$) is 2.29, while that for the grey till ($n = 13$) is 2.61, which shows that the matrix of both tills is very poorly sorted. The histogram plot of the sorting characteristics of the matrix of the olive and grey tills presented in Figure 8.4B shows this slight differentiation.

(iii) Inclusive Graphic Skewness (Sk_I).

The Inclusive Graphic Skewness gives an indication of the symmetry of the particle-size distributions. It is a much more sensitive indicator than the parameters used to measure the central portion of the distribution. A symmetrical distribution has a skewness value of 0.0, while a curve with a tail in the coarse grains has a negative value with a limit of -1.0. Particle-size distributions with a tail in the fine grains have a positive value.

The variations in the values of skewness in the olive and grey tills are shown in Figure 8.4C. The mean values of skewness for the

olive and grey tills are -0.12 and -0.07 respectively, which indicate that the tails of the olive till distributions comprise coarser material than the grey. However, the histogram shows that the data are positively skewed and that the mean value is influenced by this; the graphic representation shows the modal peaks for both tills to be close together, both falling within the "symmetrical" class as defined by Folk and Ward (1957). These results suggest that the value for skewness cannot readily be used as a diagnostic factor in differentiating the tills.

(iv) Graphic Kurtosis (K_G).

The Graphic Kurtosis is a measure of the ratio between the spread in the central part of the particle-size distribution and the spread in the tails (Folk 1966), and as such describes the departure of the particle-size curves from normality. Using this measure, normally distributed curves have a K_G of 1.0 (the distribution is said to be mesokurtic, the values ranging from 0.9 to 1.09); if the central part of the distribution is better sorted than the tails the curve is said to be leptokurtic (K_G values >1.1), while if the tails are better sorted than the central portion, the curve is flat-peaked or platykurtic (K_G values <0.89). In general, strongly platykurtic curves are often bimodal, with sub-equal amounts in the two modes, thus giving a "saddle" distribution (Folk 1966).

The mean K_G values for the olive and grey tills are 0.89 and 0.82 respectively and the variations in K_G values for all the till samples are presented in Figure 8.4D. These data show that the modal peaks for both olive and grey till are similar, both falling within the platykurtic class of Folk and Ward (1957). The results suggest

that the K_G parameter does not provide a diagnostic measure for differentiating the two tills.

In an attempt to identify any inter-relationships that may exist between the particle-size parameters of the olive and grey tills, scatter diagrams were constructed, the four particle-size parameters being plotted against each other (cf. Folk and Ward 1957; Landim and Frakes 1968). This results in six possible diagrams and these are presented in Figures 8.5 to 8.10. Inspection of the diagrams indicates that three (Figures 8.5, 8.6, 8.7) possess a well-developed linear relationship. To evaluate these relationships correlation and regression analyses were carried out on the data using the standard techniques outlined in Norcliffe (1977); the results are discussed below.

(1) Sorting (σ_I) versus Mean Size (M_Z)

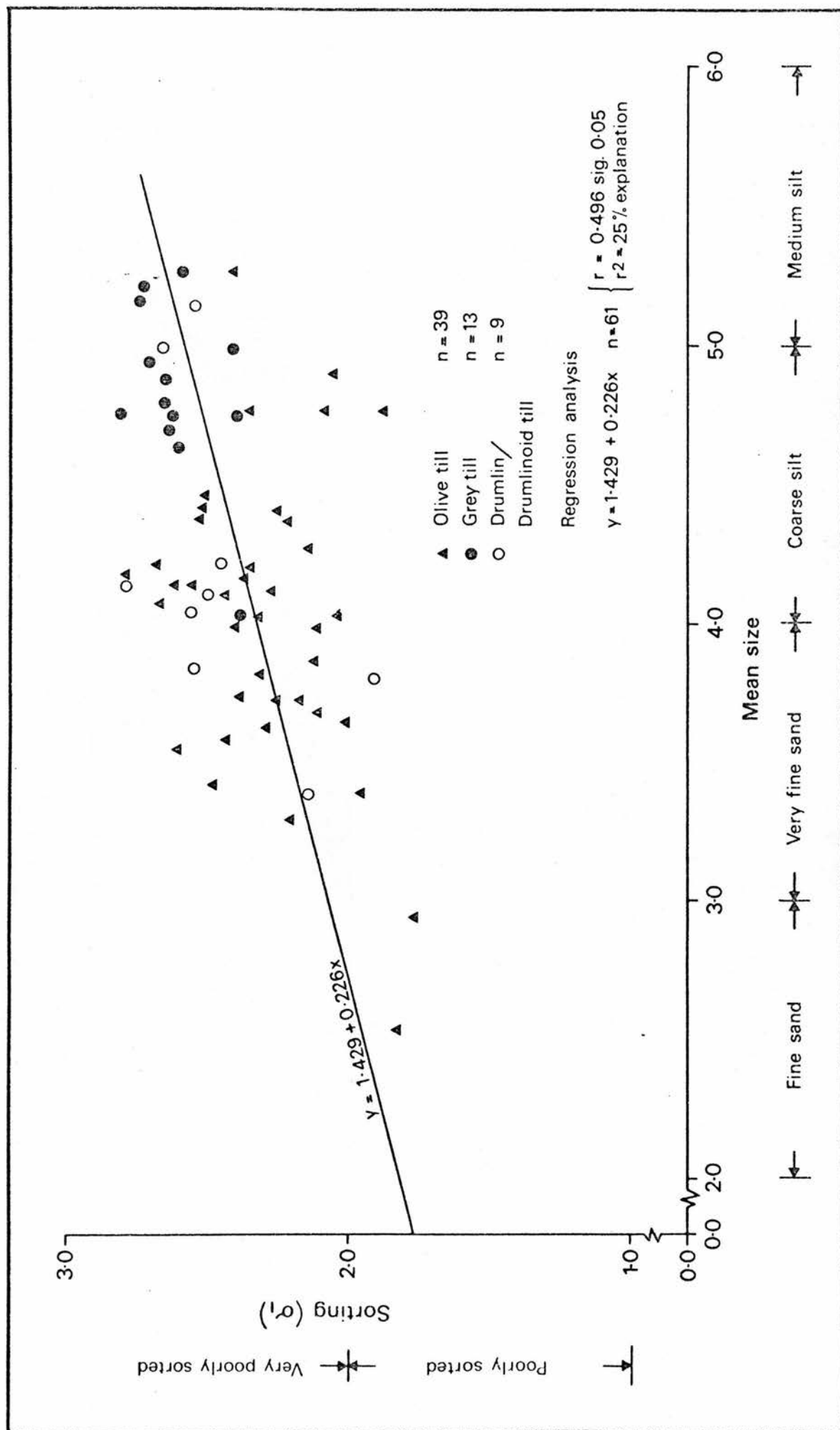
Visual inspection of the histograms shown in Figure 8.4 reveals that they are only slightly positively skewed and may therefore be analysed using Pearson's r correlation coefficient and regression. To check for any differences, however, the data set was also analysed using the equivalent non-parametric test (Spearman's Rank Correlation); the results showed the same correlation coefficient as that provided by Pearson's r .

Results of the analysis on all samples (Figure 8.5) indicate a positive linear correlation with a correlation coefficient (r) of + 0.496, which is significant at the 0.05 level. The coefficient of determination (r^2) shows that the correlation explains 25 per cent of the distribution. The regression line is defined by:

$$\sigma_I = 1.429 + 0.226 M_Z .$$

Figure 8.5

Scatter diagram of sorting against mean size
parameters.



This relationship indicates that as the particle-size of the till matrix increases, then it becomes better sorted. More specifically, the scatter diagram shows that the grey till samples (except for the single atypical sample described above) and the "text-book" drumlin tills are clearly differentiated from the olive till and drumlinoid till. Therefore, a separate regression analysis was carried out on the olive tills alone in order to see if the grey till results were in any way influencing the overall correlation and the gradient of the regression line. A similar analysis on the grey till was not possible owing to the small sample size. An r value of + 0.264 is not significant and the r^2 value is correspondingly much reduced, giving only 6.9 per cent explanation. These results suggest that in terms of the σ_I and M_Z relationships, the two tills cannot be differentiated with any degree of confidence.

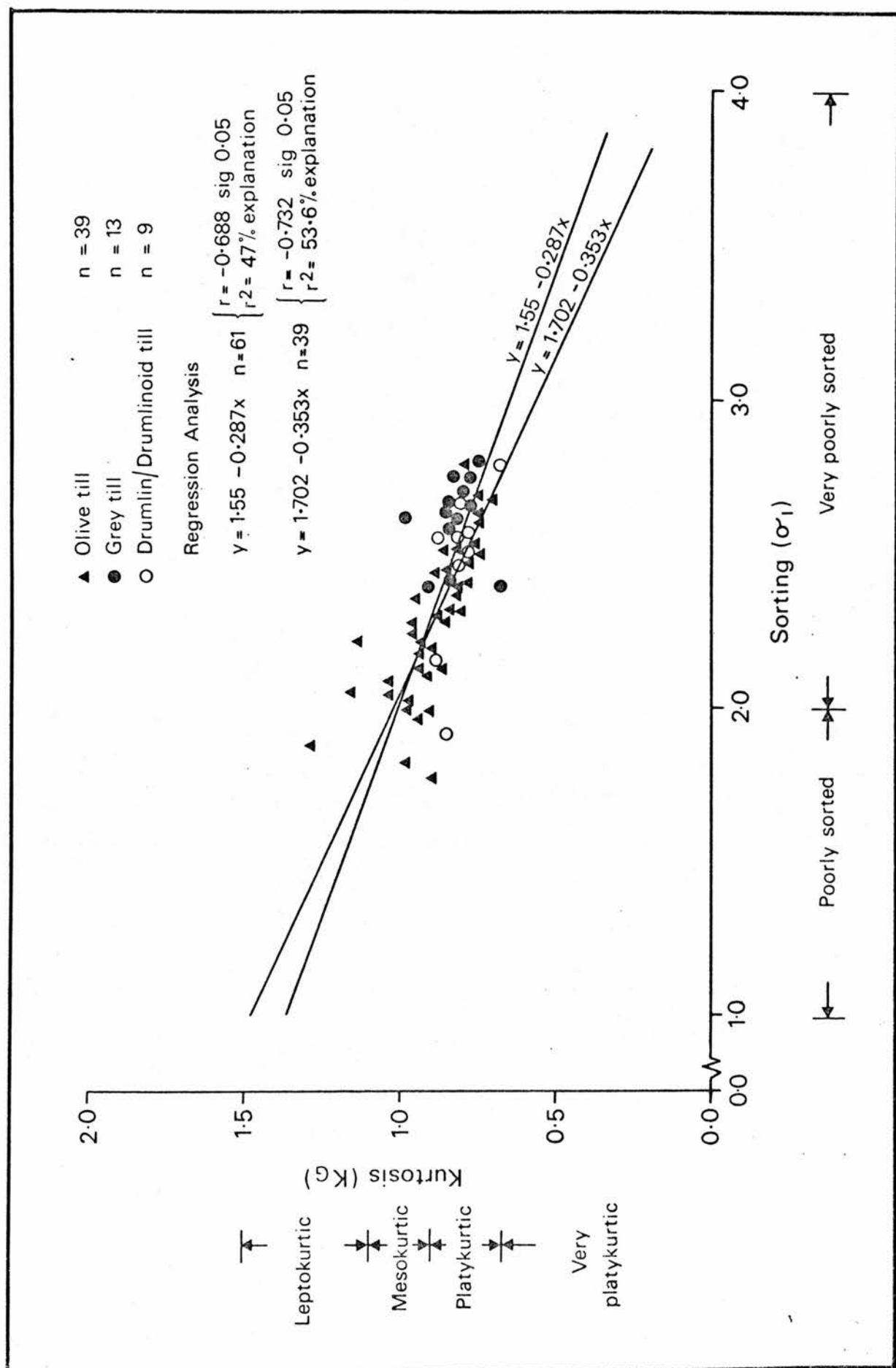
(ii) Kurtosis (K_G) versus Sorting (σ_I)

The distribution of the data included in this analysis also approximates normality and therefore correlation and regression procedures may be applied. For all samples, an inverse linear relationship exists between the K_G and σ_I parameters of the two tills. The regression line is given by the equation $K_G = 1.55 - 0.287 \sigma_I$ (Figure 8.6) and the correlation coefficient is - 0.688, which is significant at the 0.05 level; the r^2 value indicates that 47 per cent of the distribution is explained by the analysis.

In general terms the relationship suggests that the more poorly sorted the till matrix, the lower the K_G values (i.e. the distribution curves become more platykurtic). More specifically, the olive and grey tills show a partial separation on the scatter diagram. The

Figure 8.6

Scatter diagram of kurtosis against sorting parameters.



grey till samples show very poor sorting characteristics and a corresponding platykurtic distribution, while the olive till samples straddle the poorly sorted - very poorly sorted boundary and show largely mesokurtic characteristics. There does not seem to be any differentiation between the drumlin and drumlinoid samples.

In an attempt to see whether the grey till samples were affecting the regression line gradient, the olive till samples were again analysed separately. The equation for this regression line is $K_G = 1.702 - 0.353 \sigma_1$, the r value is -0.732 (significant at the 0.05 level) and the r^2 value indicates 53.6 per cent explanation. Although the level of explanation is increased (due to the exclusion of two grey till samples that fall well away from the initial regression line), the gradient of the regression line is only slightly affected, which suggests that within this relationship the grey tills do not constitute a widely separate population.

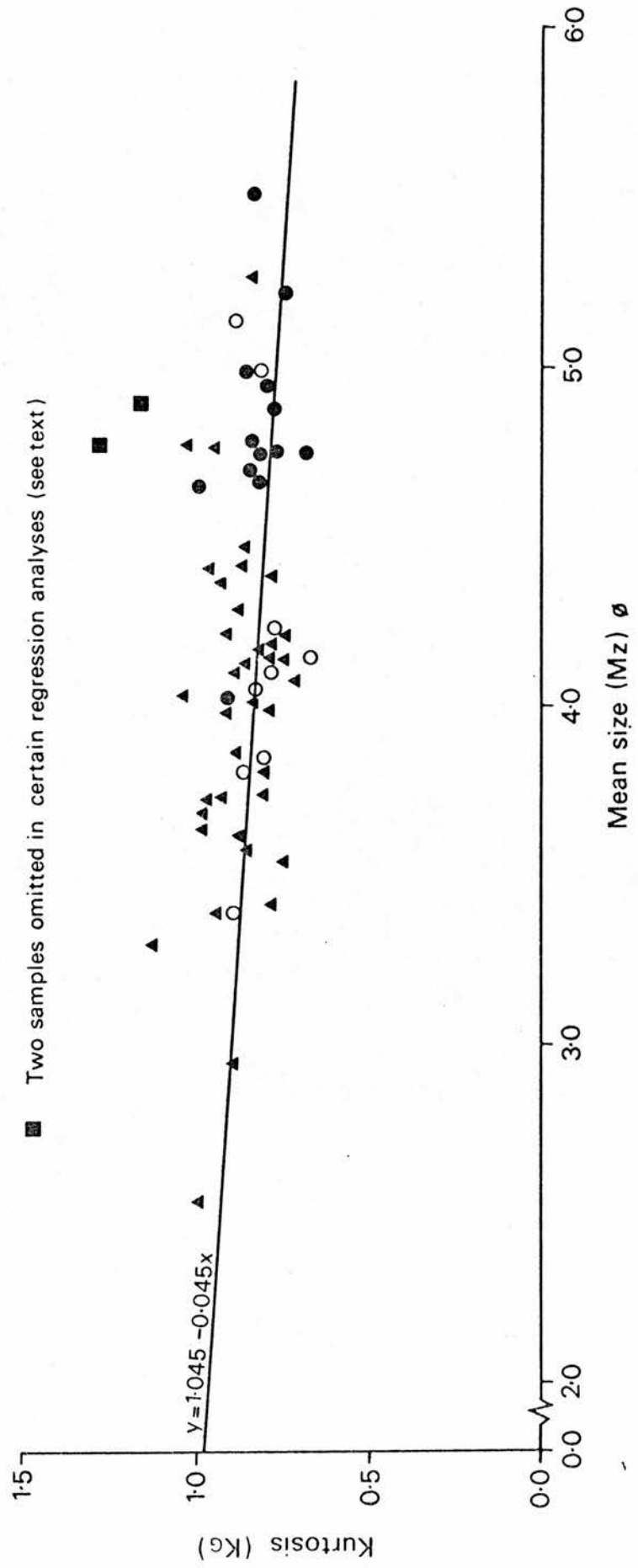
(iii) Kurtosis (K_G) versus Mean Size (M_z)

Inspection of the scatter diagram (Figure 8.7) indicates a linear relationship, which is slightly inverse, between the K_G and M_z parameters. This demonstrates that as the tills become finer grained, then they become slightly more platykurtic in their distribution; this phenomenon was also observed by Landim and Frakes (1968). The grey and olive tills show a clear separation in Figure 8.7, with 11 of the grey till samples falling in the platykurtic class, while at the same time straddling the coarse silt/medium silt (5.0ϕ) M_z boundary. The olive till samples, having coarser tails to their distributions, tend to span the platykurtic - mesokurtic boundary. In addition, the drumlin and drumlinoid samples show a clear separation

Figure 8.7 Scatter diagram of kurtosis against mean
size parameters.

▲ Olive till	n = 39	Regression analysis $y = 1.045 - 0.045x$ $n = 59$ $\left\{ \begin{array}{l} r = -0.292 \text{ sig. } 0.05 \\ r^2 = 8.5\% \text{ explanation} \end{array} \right.$
● Grey till	n = 13	
○ Drumlin/ Drumlinoid till	n = 9	

■ Two samples omitted in certain regression analyses (see text)



within themselves, but inspection of the diagram indicates that this is only a function of the differences in M_z .

Two samples, however, both from the olive till, stand out as being significantly different from this general relationship. The samples are atypical in that they possess a leptokurtic distribution, while at the same time they have a fine-grained M_z (4.76 ϕ and 4.89 ϕ). These samples were taken from the central part of the area covered by the cross-valley ridges; one sample was excavated from an inter-ridge section by Carsphairn village (NX 553932) and the second from a bedrock-controlled cross-valley ridge by Kendoon Loch (NX 608907). In terms of colour, stoniness and induration, the exposures from which the samples were taken appeared no different from other olive till sampled in the immediate vicinity. Thus, no explanation can be offered for the particularly high percentages of coarse silt size particles (4.0 to 5.0 ϕ) found in these samples.

As the distributions of the K_G and M_z values approximate normality, Pearson's r was employed to test the significance of the visually determined trend. Using all samples ($n = 61$) an r value of -0.116 was obtained ($r^2 = 1.3$ per cent explanation), which was not significant to reject the null hypothesis of no correlation between K_G and M_z . This apparently anomalous result is due largely to the atypical nature of the two samples mentioned above. The particle-size parameters of these two samples are sufficiently atypical to affect the calculation of the r value by cancelling out the low gradient inverse relationship, causing the correlation to be pulled toward a positive trend. It was therefore decided to remove the two samples from the data set and run the test again. The resulting

r value was -0.292 ($r^2 = 8.5$ per cent), which is significant at the 0.05 level; the equation for the regression line is

$K_G = 1.045 - 0.045 M_Z$ and this is plotted on Figure 8.7.

In order to test the effect of the grey till values on those of the olive, the two data sets were analysed separately (excluding the drumlin and drumlinoid data) by correlation and regression procedures. The results are indicated on Figure 8.7. The r value for the olive till ($n = 37$) is not significant (-0.195) and the r^2 value explains only 3.8 per cent of the distribution. Similarly the results for the grey till ($n = 13$) are -0.344 (not significant) and 12 per cent respectively. The absence of any significant correlation between the K_G and M_Z values is probably due to the very small variance in the K_G values for both tills. Therefore, in terms of the M_Z and K_G values, no definite statistical relationship can be determined.

(iv) Other results

The three remaining scatter diagrams (Figures 8.8, 8.9, 8.10) show no significant correlations, this being largely a reflection of the lack of difference within the skewness values between the two tills. The only separation that does appear occurs in the plot of Sk_I values against M_Z values (Figure 8.8). Here, the grey till samples show a certain degree of separation, with negative skewness values associated with high M_Z values (5.0ϕ).

8.3 DISCUSSION OF PARTICLE-SIZE ANALYSIS RESULTS

Kurkal (1971), Dreimanis and Vagners (1972), Boulton and Paul (1976) and Dreimanis (1976) have all drawn attention to the fact that

Figure 8.8 Scatter diagram of skewness against mean
size parameters.

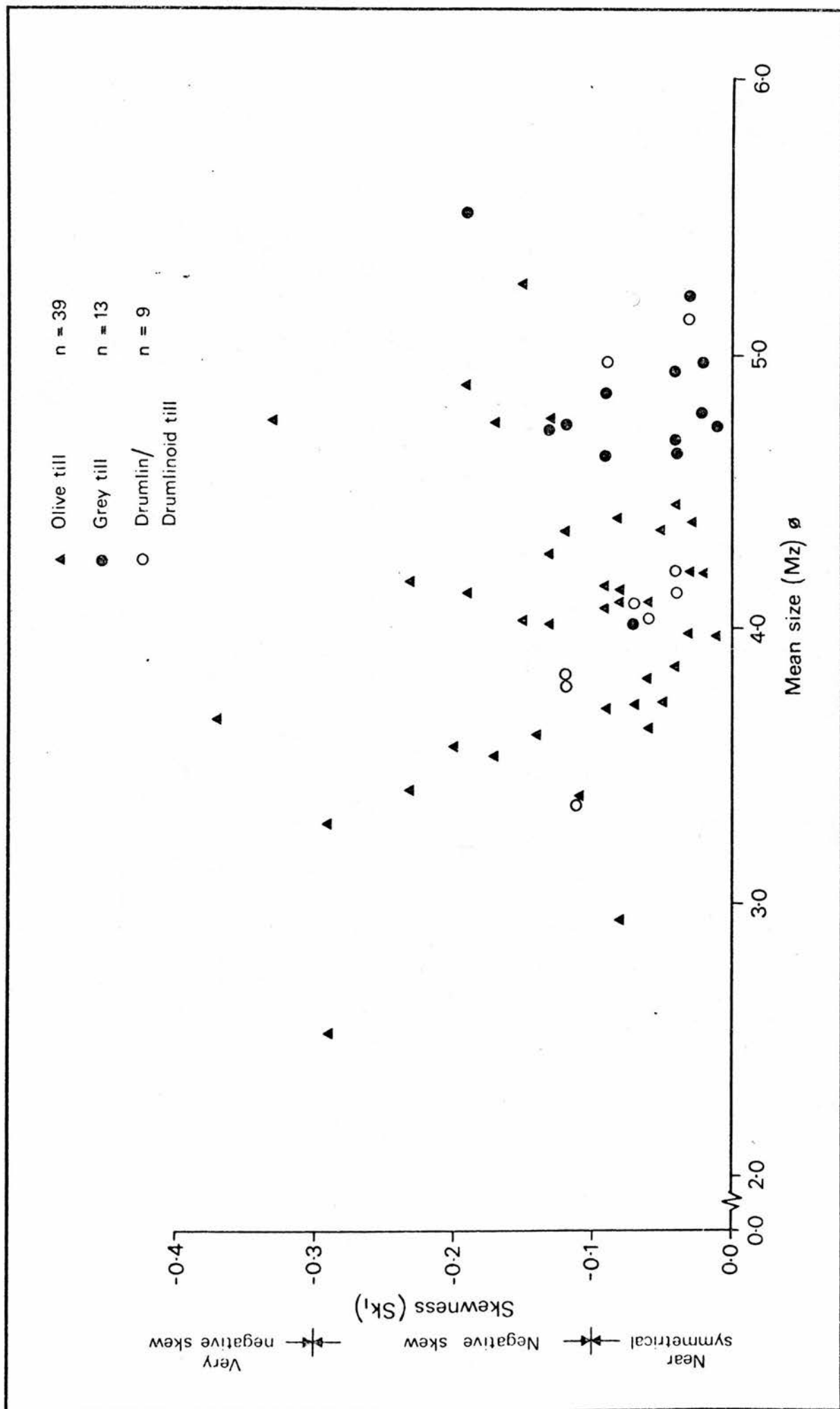


Figure 8.9

Scatter diagram of kurtosis against skewness parameters.

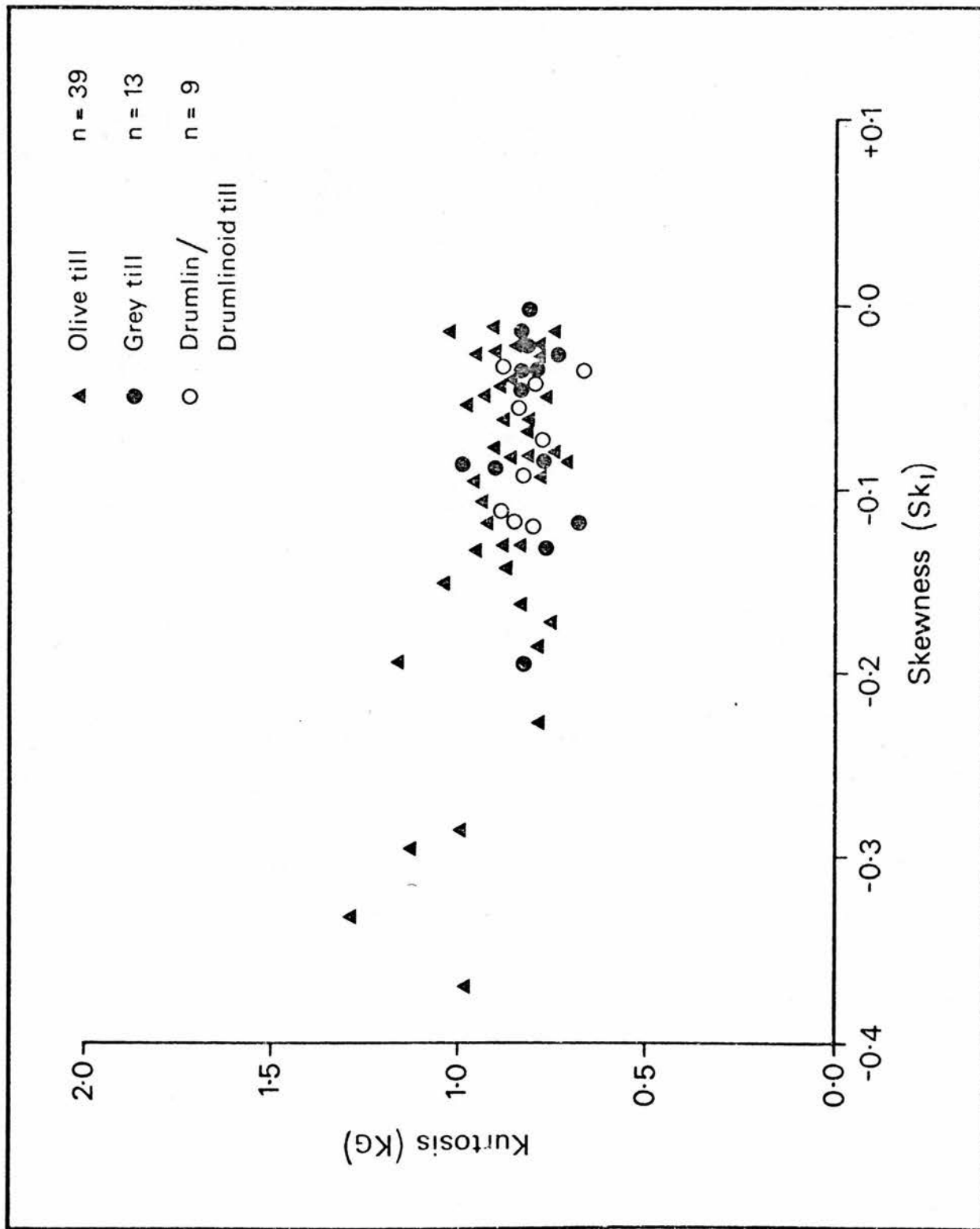
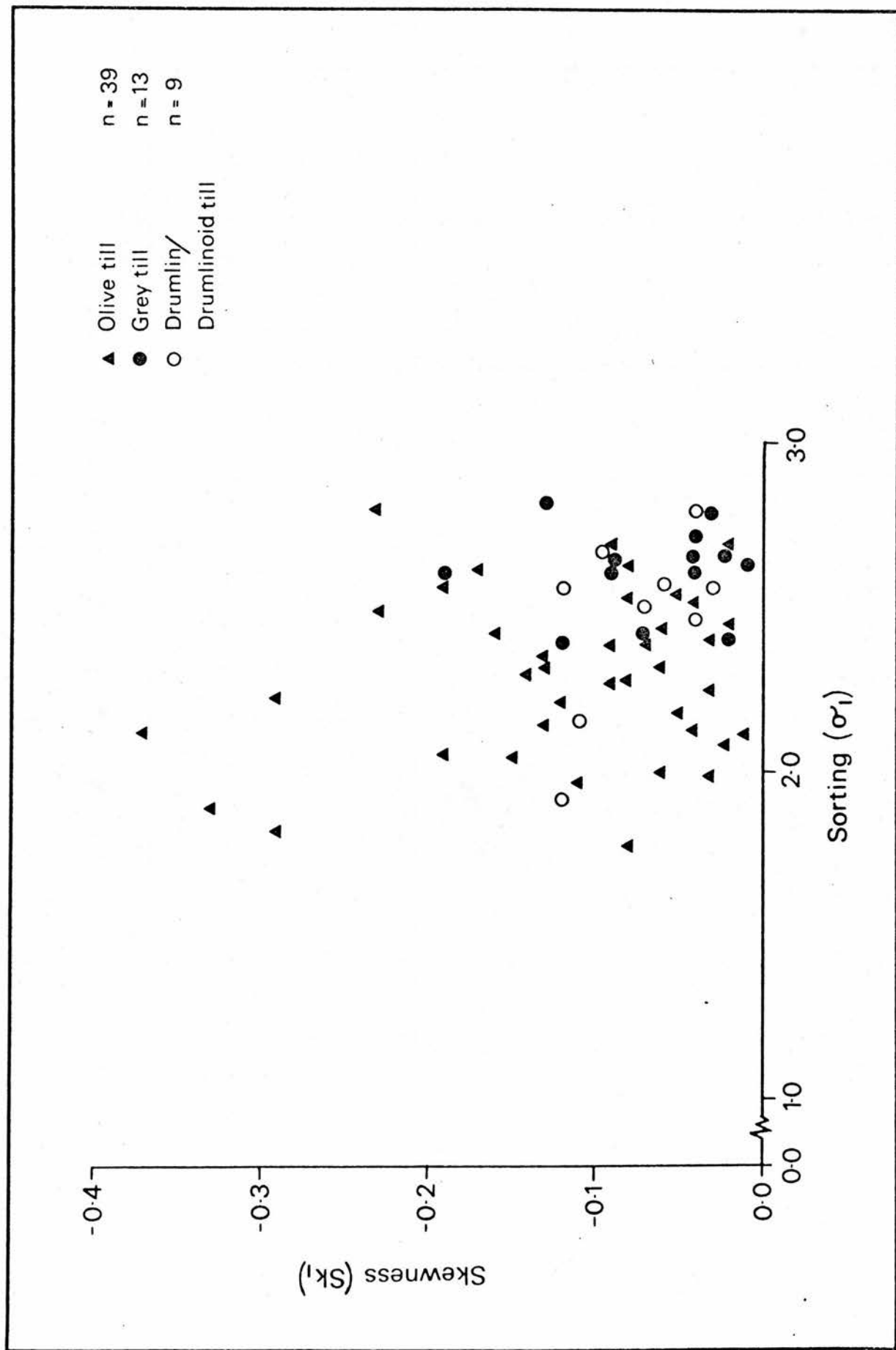


Figure 8.10 Scatter diagram of skewness against sorting parameters.



the texture of any till is dependent on four major factors.

- 1) The lithological composition of the matrix and the clasts in till, is a reflection of the lithology of the source rocks.
- 2) The mode of transport, whether sub-, en- or supraglacial is, in turn, reflected in the comminution and possible sorting of the rock and mineral fragments.
- 3) The processes ^{that} operate during deposition of the till.
- 4) Post-depositional changes ^{that} occur after exposure of the till to subaerial processes.

These variables will be considered in turn in an attempt to assess their influence on the particle-size properties of the tills analysed. The lithology of the bedrock over which any glacier passes is fundamental in determining the rate of comminution of eroded debris as well as the relative proportions of the silt and clay size fractions. The two most important bedrock contributors to the tills of the Carsphairn area are the Ordovician greywacke sediments (which include conglomerates and thin beds of shale and mudstone) and the granite/ granodiorite rocks of the Cairnsmore of Carsphairn pluton. The major mineral components of these rocks that crop out on or adjacent to the former ice-shed in the Carsphairn area have already been outlined in some detail in Chapter 2. The relative differences in the mineral composition of these two suites of rocks have led to the production of a complex particle-size distribution in the tills, a distribution that is in many respects a function of their location with reference to the respective outcrops.

The grey till is the lowest unit of drift that crops out in the

Carsphairn Lane - Water of Deugh - River Ken area. Since these valleys are floored by greywacke rocks it is certain that the particle-size properties of the grey till have been strongly influenced by the mineralogical composition of the bedrock (cf. studies of a similar nature by Holmes 1952; Gillberg 1965, 1967; Linden 1975; Haldorsen 1977). The upper, olive till unit, however, whose stratigraphical position indicates that it was transported at a higher level in the ice, should be increasingly affected in its composition by granitic debris. This somewhat simplistic argument has to be viewed with caution, however, since the presence of large percentages of quartz particles in any one of the tills need not necessarily constitute proof of its derivation from a granitic source rock, owing to the high percentages of quartz particles present in the greywacke rocks that crop out in this area.

In order to test this argument a lithological analysis was carried out on the 1.25 to 2.0 ϕ (medium sand) size fraction of the two tills at the same time as the roundness analysis (Chapters 2 and 10). A total of 100 grains from each of 52 samples (39 from the olive till and 13 from the grey) was counted and the results are shown in Table 8.4. Two lithologies (quartz grains and greywacke rock fragments) dominate the analysis, comprising between 96 and 100 per cent of each sample. Feldspar grains and porphyrite rock fragments (from dykes cropping out in the former ice-shed zone) form only very minor constituents of each sample. Although the sample sizes are small, certain differences are observable. The grey till samples are dominated by greywacke fragments, while the olive till shows an even split between these and the quartz particles. This implies that the

Table 8.4 Lithological composition of the 1.25 to 2.0 ϕ size fraction of tills from the Carsphairn Lane - Water of Deugh - River Ken area (drumlin and drumlinoid samples excluded).

	Quartz particles dominant	Greywacke fragments dominant
Olive till (n = 39)	21	18
Grey till (n = 13)	2	11

olive till has been enriched to some degree by quartz particles in the 1.25 to 2.0 ϕ size range, and that this source may be the Cairnsmore of Carsphairn and Craig of Knockgray granitic bedrock. The high percentage of sand-size material (4.0 to 0.0 ϕ), which is reflected in the bimodal nature of many of the olive till particle-size frequency distributions, and its low coefficient of variation lend support to this interpretation.

The effects of comminution during glacial transport, its dependence upon the lithology of source rocks, and its manifestation in the particle-size distribution of tills, have been recorded by Dreimanis and Vagners (1965; 1969,a,b; 1971; 1972) from Ontario, Canada. They showed that newly eroded debris was characterised by a dominant clast mode in the range -3 to -6 ϕ , but as transport and comminution proceeded this mode was progressively reduced and a second mode developed in the silt range (4 to 6 ϕ), which eventually became dominant. This latter mode was defined by Dreimanis and Vagners as the "terminal-grade" of minerals within the source rocks. Similar results have been described by Järnefors (1952) from two tills located

near Pajala in Sweden. Here the tills are dominated by coarse and fine sand particles (0.0 to 1.0 ϕ and 2.0 to 3.0 ϕ respectively). Järnefors suggested that this distribution was a function of the monogranular nature of the particles, which become resistant to glacial grinding once they reached the ca. 3.25 to 4.25 ϕ size range. Elson (1961) has also stated that particles of sand created in the initial crushing operation are not reduced further by abrasion. Moreover, Drake (1968) has argued that the sand-rich leptokurtic basal tills in New Hampshire are intrinsically related to the crushing of the granite bedrock (from which they were derived) to the size of mineral grains that are in the sand range.

It has not been possible in the present study to identify the clast and terminal-grade modes of Dreimanis and Vagners for two reasons. First, the material coarser than 0.0 ϕ was not analysed. Secondly, as proved by the studies of glacial erratics in the area, the distance of transport of the tills constituting the cross-valley ridges has been too short to identify any specific terminal-grades of the bedrock minerals; this partly accounts for the bimodal and multimodal nature of the particle-size distributions, with rock fragments being well represented in various size classes as well as each constituent mineral occupying its own fine-grained mode. In the studies mentioned above, quartz is considered to be resistant both physically (due to the absence of cleavage properties and to its hardness of 7 on Moh's scale) and chemically to any change in its shape and as such is introduced into any superficial sediment system as particles of sand (Smalley 1966; Smalley and Krinsley 1974) and is expected to remain as such. However, it is possible that the

grinding and crushing action of glacier ice is sufficient to reduce sand-size grains to very small dimensions and that the resulting silt/clay-size material can contribute significantly to the composition of many drift deposits.

Dreimanis and Vagners (1969b, 1972) have suggested that coarse silt-size material (4.0 to 5.0 ϕ) is the most common terminal-size range for minerals that had their original grain size coarser than 4.0 ϕ prior to comminution, and argue that this explains why silt is the most common particle-size in the matrix of tills that have undergone long distance transport. However, in the present study, coarse silt is the modal particle-size for both tills, but the minerals in these deposits have not reached their terminal-grades owing to their very short distance of transport. Thus it would seem that an alternative source for the silt-size material is required.

It is suggested that the well-developed microcrystalline matrix of the greywacke rocks in combination with the crushing by glacier action of clast-size particles, of granodiorite as well as greywacke, has provided an important source for the silt- and clay-size particles in the matrix of the tills in the Carsphairn area. This view is supported by work carried out on the composition of silt- and clay-size particles derived from formerly glaciated areas (Kuenen 1969; Vita-Finzi and Smalley 1970; Drake 1971; Cabrera and Smalley 1973). These workers have suggested that the high pressures generated at the ice-bedrock interface are sufficient to produce a fine-grained rock flour (defined by Vivian (1970) as fresh mineral fragments smaller than 3.25 ϕ in diameter), leading to an enrichment of the clay- and silt-size fraction of tills with crushed mineral fragments rather than

with clay mineral silicates. The close association of loess deposits with areas of former continental glaciation lends support to this hypothesis. In addition Goldthwait (1971, p.10), quoting a personal communication from Wilding (1970), states that " . . . 60 to 90 per cent of the silts in many tills comprise mainly freshly ground quartz, calcite or feldspar, rather than clay minerals".

These considerations are important, but they must also be viewed in the light of conclusions presented by Emerson (1917), Goldthwait and Kruger (1938), Kujansuu (1967), Kaitanen (1969), Feininger (1971) and Rosenqvist (1975a,b), who have all suggested that the fine-grained components of till may partly reflect the incorporation of pre- or interglacial bedrock decomposition products, which would be rich in clay mineral silicates. Beaumont (1972), in a study of the clay mineralogy of tills from eastern Durham, estimated that between 65 and 75 per cent of the clay-size fraction comprised clay minerals and that these were derived from the crushing of Coal Measures sediments.

That clay minerals (less than 9μ diameter) are present in the soils developed on the olive till in the Carsphairn area has been proved by X-ray diffraction and thermal analyses carried out by Bown (1973). In his consideration of the soils occurring in the Galloway region, Bown has shown that in the Ettrick and Carsphairn soil series (which covers the area from which the olive till samples were recovered) the dominant clay minerals comprise illite and chlorite with some kaolinite. However, he gives no indication of the percentages involved, nor are the quartz and feldspar fractions considered in the results. Thus, any meaningful comparisons between the two groups of minerals is not possible.

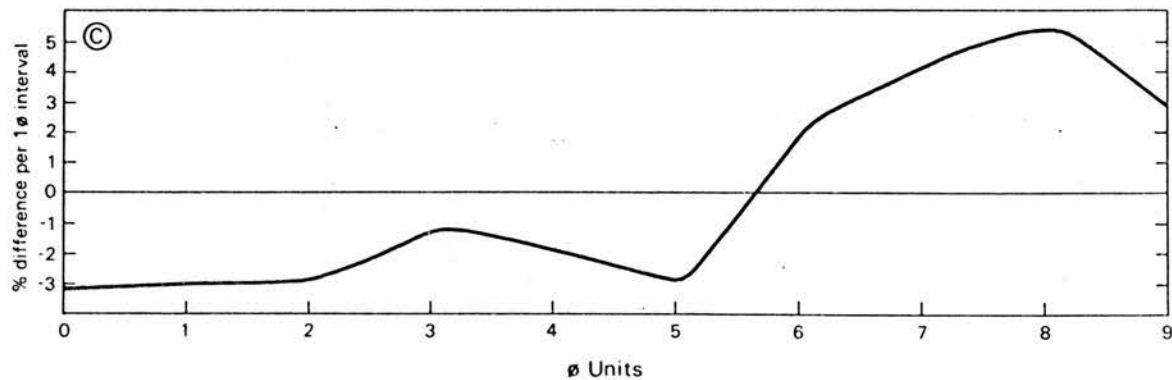
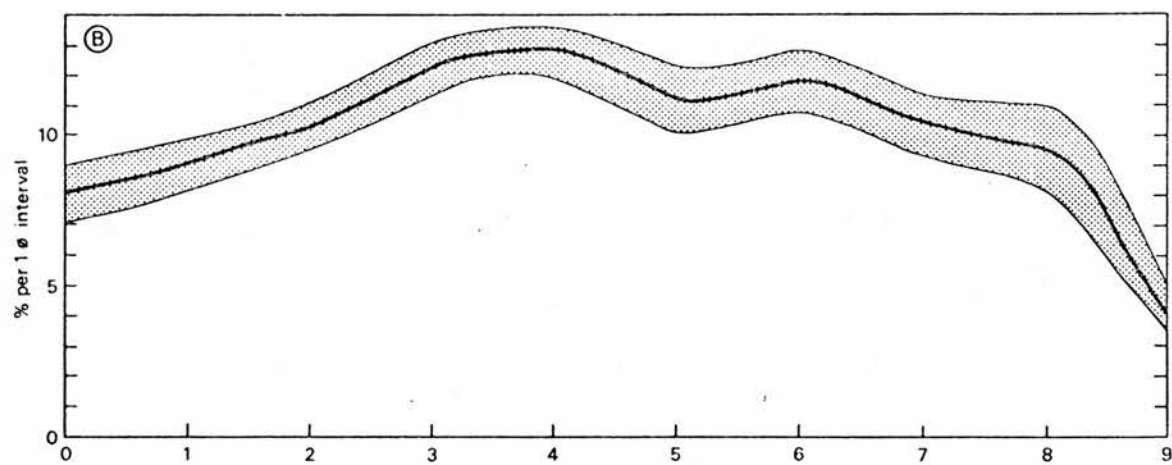
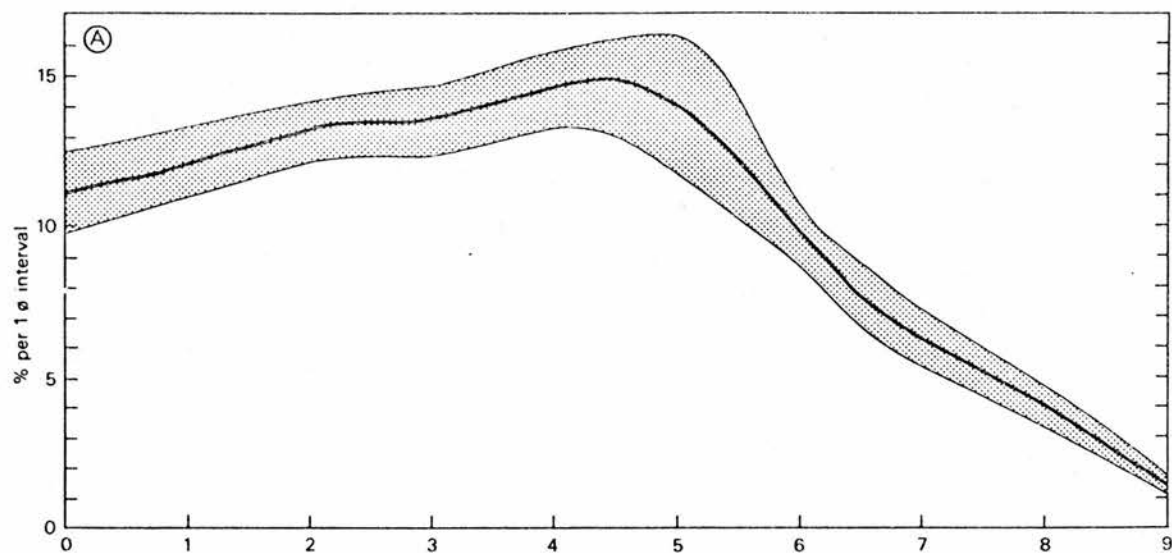
With reference to these observations, however, it should be expected that any preglacial or interglacial weathering products would have been rapidly removed from the area by initial glacier activity, owing to their friable and non-resistant nature (see Appendix III for further discussion). Therefore it should be anticipated that the tills deposited in the Carsphairn area, being the final deposition products from the Late-Devensian glaciation, would largely reflect the composition of the "fresh" bedrock (as well as till deposited from previous glaciations) rather than its weathering products. Further, the abundance of any clay minerals from "fresh" bedrock sources would be much reduced by the effects of thermal metamorphism (a process that tends to eliminate clay minerals (Williams, Turner and Gilbert 1954)), and by the high percentage of quartz detritus in the matrix of the greywacke rocks in the area. Also, Dreimanis (1961) has shown that the matrix of tills derived from igneous rocks produces very few clay mineral particles. Moreover, the clay mineral silicates recorded by Bown (1973) from the Carsphairn area were recovered from sub-surface soil samples, thus it is quite possible that these clay minerals have been produced by post-depositional weathering processes.

If it is accepted that in the Carsphairn area (i) a large percentage of the silt- and clay-size particles that comprise the matrix of the tills is rock flour and (ii) that the composition of the thermally metamorphosed and diagenetic epimatrix of the greywacke bedrock has influenced the type of particle produced during glacial erosion, transport and deposition, then certain inferences may be made to explain the relative amounts of silt and clay in the two tills of the area.

The plot of Inclusive Standard Deviation against Graphic Mean for the particle-size distributions (Figure 8.5) shows an enrichment in the fine silt- and clay-size ranges of the grey till as compared to the olive. This difference is more strikingly apparent in Figure 8.11A and B where the average particle-size distributions for the olive and grey tills are shown respectively. Further comparison between the particle-size distributions of the two tills is facilitated by plotting the percentage differences, per 1 ϕ interval, between the average particle-size distributions mentioned above (Figure 8.11C). This clearly shows an enrichment in the fine fraction (in particular those less than 7 ϕ diameter) of the grey till compared to the olive till, where depletion in the coarser fraction occurs. The most reasonable explanation for this phenomenon, in the light of the arguments presented above, is that the greywacke bedrock was comminuted to the fine silt- and clay-size range in the zone of traction at the ice-bedrock interface, and that these particles comprise rock flour (comminuted quartz, feldspar and rock fragments). Boulton (1978) demonstrated similar patterns in his study of subglacial tills from glaciers in Iceland, Switzerland and Spitzbergen.

The production of large quantities of rock flour may also account for the similar mean percentage silt-size values in both the olive and grey tills. If this is the case, then it suggests a certain degree of abrasion during transport of the olive till debris, a suggestion that is in accord with the evidence presented on the roundness characteristics of the olive till particles (see Chapter 10). The particle-size differences between the two tills may thus be in part accounted for if the olive till debris was rapidly transferred to

- Figure 8.11
- A. Mean weight percentages per 1.0 ϕ interval of the olive till (39 samples);
 - B. Mean weight percentages per 1.0 ϕ interval of the grey till (13 samples) - shaded area gives ± 2 S.E. at each 1.0 ϕ interval;
 - C. The difference between curves A and B indicating a deficiency in fines less than 5 ϕ for the olive till.



a low englacial position where the processes of comminution would be less intensive than in the basal zone of traction (where the grey till debris was transported).

It must be stressed that the texture of any till matrix may also have been influenced by depositional and post-depositional agencies that may affect, and in some cases significantly alter, the particle-size properties. In terms of changes during deposition, Boulton *et al.* (1974) showed that the upper horizons of lodgement till revealed at the retreating margin of Breidamerkurjökull, SE Iceland contained higher percentages of fines (40 per cent of the fraction less than 4 ϕ) than the underlying till (15 - 20 per cent). This increase in the fine fraction was attributed to the former horizon having been subject to subglacial shearing in which dilation and inter-particle crushing had occurred. These observations are important, for they demonstrate that the processes by which tills may become enriched in fines may occur other than by crushing during glacial transport. It is therefore possible that the high percentages of silt in the olive till may also be, in part, a response to a similar mechanism (this point will be developed in detail in Chapter 12).

That the particle-size properties of till may be influenced by post-depositional downward percolation of water, which may translocate fine-grained particles, has been demonstrated by Boulton and Dent (1974). They have shown that lodgement till exposed beyond the margin of Breidamerkurjökull loses up to 10 per cent of the silt and clay fraction from its surface layers within the first year of exposure. This material was redeposited at greater depth, forming a dense silty horizon. Somewhat similar processes have also been

discussed by several workers with regard to the deposition of supraglacial till (e.g. Gillberg 1955; Elson 1961; Boulton 1968, 1971, 1972a; Drake 1971; Vorren 1977). These workers have concluded that most of the silt and clay particles in supraglacially deposited tills are washed out by meltwater action, leaving a deposit dominated by sand- and gravel-size particles.

It has been argued above that the silt- and clay-size fractions of the tills in the Carsphairn area are dominated by rock flour. The particles comprising this material have been shown by various workers to lack the long-range, active bonding strengths of clay minerals (Smalley 1971; Cabrera and Smalley 1973; Smalley 1976; Price, pers. comm. 1978). The bonding between clay- and silt-size rock flour is short range, inactive and easily disturbed. Clay minerals also possess strong electrolytic and electrostatic forces, which tend to enhance their bonding strengths, in some cases to the extent of creating impervious layers (Price, pers. comm. 1978). If the olive till had undergone extensive washing and sorting in a supraglacial environment then the silt-size fraction, having low bonding strength, would have been markedly reduced. This, however, does not accord with the olive till having a relatively high silt content ($\bar{x} = 31.5\%$) and the modal peak of its matrix in the coarse silt-size range, which further supports the contention that the olive till is of subglacial origin.

8.4 SUMMARY AND CONCLUSIONS

In general terms, the particle-size distribution of the grey till in the Carsphairn area may be said to be characterised by

a fine-grained matrix (in the coarse silt range) that is very poorly sorted and possessing a platykurtic distribution, which is slightly negatively skewed. The olive till matrix is fine-grained (again in the coarse silt range), very poorly sorted and has a platykurtic to mesokurtic distribution that is almost symmetrical.

It has been argued that the differences in texture of the two tills, as shown by the analyses, may be due to:

- 1) the nature of the bedrock source material. The greywacke rocks produced debris rich in silt- and clay-size particles, composed dominantly of quartz, feldspar or rock fragments, in the grey till, while granitic bedrock produced an enrichment of quartz material of fine sand- and silt-size in the olive till.
- 2) the environment of transportation. The particles comprising the grey till matrix resulted from comminution in the zone of traction, leading to an enrichment of clay- and silt-size particles. The particles comprising the olive till matrix, although originating at the base of the ice, were conveyed to, and transported at a low englacial position in the ice. Thus the particles suffered less comminution than those of the grey till. However, the restricted transport of debris in the Carsphairn area argued for in Chapter 5 suggests that the influence of glacial transport may have been limited.
- 3) changes during till deposition. Subglacial shearing, promoting dilation and interparticle crushing, during deposition increased the percentage of silt-size particles in the olive till.

The genesis of the cross-valley ridges may also be partly explained in terms of the particle-size characteristics of the tills.

- 1) If the cross-valley ridges were formed supraglacially, then the olive till would have been expected to possess lower percentages of silt-size material than they do. As the two tills possess very similar percentages of silt, then a subglacial formation for the olive till, and in turn for the cross-valley ridges, is implied.
- 2) A close affinity has been demonstrated between the particle-size distribution of till samples from the valley-fill deposits, the cross-valley ridges, the inter-ridge areas and the drumlinoid landforms. This evidence suggests a genetic relationship in that as drumlins are known to be formed subglacially then it would seem logical to expect the cross-valley ridges also to be formed in the same environment.

CHAPTER NINE
ANALYSIS OF CERTAIN GEOTECHNICAL
PROPERTIES OF TILLS FROM THE
CARSPHAIRN LANE - WATER OF DEUGH -
RIVER KEN AREA

9.1 INTRODUCTION

The Atterberg limit characteristics of till deposits are considered to provide a good indication of the role of particle-size in influencing their geotechnical properties. Thus as an adjunct to the particle-size analysis, the Atterberg limits of the two tills in the Carsphairn area were determined on 20 randomly selected samples (grey till: $n = 3$; olive till (including samples from cross-valley ridges, valley-fill deposits and drumlinoid landforms): $n = 17$), following the procedures outlined in Chapter 3.

9.2 RESULTS AND ANALYSIS

The Atterberg limits as defined by Deere and Shaffer (1956) were used.

- 1) The liquid limit (LL) and the plastic limit (PL) are defined as the upper and lower limiting moisture contents (expressed as percentages) at which a cohesive sediment remains "plastic".
- 2) The plasticity index indicates the range in moisture content over which the sediment is "plastic", and is calculated by subtracting the value obtained for the plastic limit of each sample from that of the liquid limit. In general terms,

a sediment with a plasticity index over 50 per cent is regarded as being highly plastic material, while a plasticity index below 30 per cent indicates low plastic properties (Casagrande 1932).

Empirical experiments carried out by Casagrande (1932, 1948) have shown that many of the properties of clay- and silt-size material can be correlated with the Atterberg limits by means of the plasticity chart. In this chart the plasticity index is plotted as the ordinate and the liquid limit as the abscissa (Figure 9.1).

The results of the analysis of the three grey till samples (Table 9.1) show certain interesting relationships. Although the percentage of clay-size material is relatively high (24.7 to 29.9%), the respective plasticity indices are very low (5.0 to 6.5%). This relationship is confirmed when the results are plotted on the plasticity chart (Figure 9.1), which indicates that the till matrix may be classified as an inorganic clay of low plasticity. The low plasticity characteristics of the grey till further indicate that, when stress is applied, the till will not deform until a critical threshold is attained. This "yield stress" property may be defined as the cohesion of the till (Wilun and Starzewski 1972, p.149), which in the case of the grey till samples is of a low order.

An estimate of the angle of internal friction of the grey till may also be gained using the plasticity index results. Terzaghi and Peck (1967) have shown that a relationship exists between the angle of internal friction of moderate to low cohesive soils and the plasticity index. Values for the angle of internal friction of the grey till samples have been estimated from the graph of Terzaghi and

Figure 9.1 The modified plasticity chart (after Casagrande 1932) showing the results of the Atterberg limit tests on the grey till.

Modified Plasticity Chart (after Casagrande, 1932)

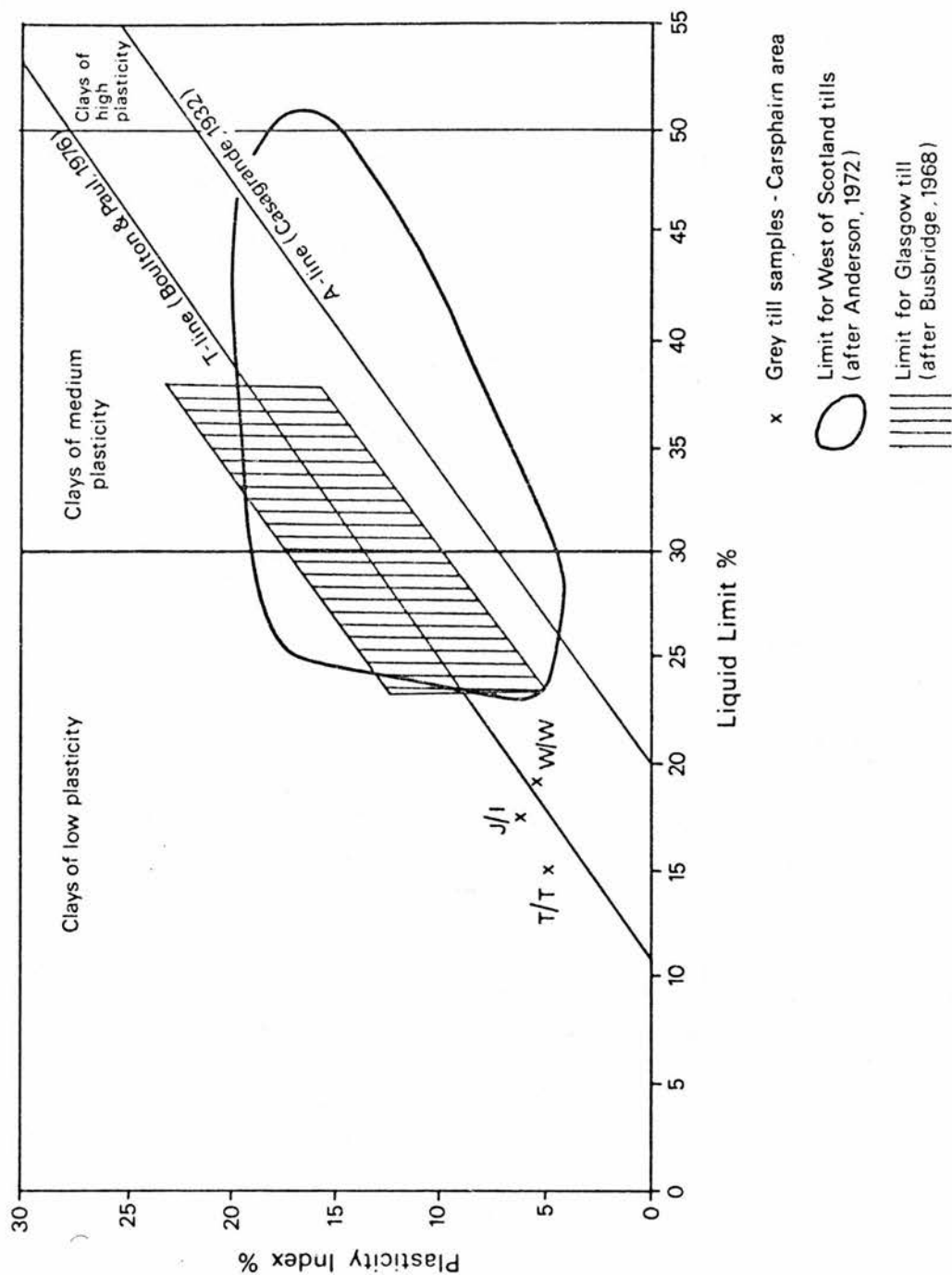


Table 9.1 Results of Atterberg limit tests on tills from the Carsphairn Lane - Water of Deugh - River Ken area and their relation to certain particle-size parameters.

Sample	% > 9 ϕ (sand and silt)	% < 9 ϕ (clay)	Plastic limit (%)	Liquid limit (%)	Plasticity index (%)
GREY TILL					
J/1	70.1	29.9	12	17.5	6.5
W/W	70.3	29.7	13	18.6	5.6
T/T	75.3	24.7	10	15.0	5.0
OLIVE TILL					
<u>Cross-valley ridges</u>					
R/R	94.4	5.6	-	-	-
O/O	93.2	6.8	-	-	-
F	90.9	9.1	-	-	-
A/D	95.4	4.6	-	-	-
J/2	91.5	8.5	-	-	-
B/3	93.1	6.9	-	-	-
M	92.7	7.3	-	-	-
N	88.0	12.0	-	-	-
P/P	94.5	5.5	-	-	-
L/L	95.8	4.2	-	-	-
Y/Y	88.5	11.5	-	-	-
A/F	95.8	4.2	-	-	-
<u>Valley-fill</u>					
O	89.7	10.3	-	-	-
P	95.0	5.0	-	-	-
<u>Drumlinoids</u>					
Q	96.9	3.1	-	-	-
Z	92.2	7.8	-	-	-
W	90.3	9.7	-	-	-

Peck (1967, p.112) and show a range between 38° and $40^{\circ} \pm 5^{\circ}$, thus demonstrating a high angle of internal friction for the deposits.

The Atterberg limit tests carried out on the 17 olive till samples, however, showed no indication of possessing plastic properties. The chief reason for this is the presence of high percentages of particles larger than 9ϕ in diameter (88 to 95%), which tend to decrease the plastic and liquid limits and consequently reduce the plasticity index (Dumbleton and West 1966).

9.3 DISCUSSION OF THE ATTERBERG LIMITS ANALYSIS

Numerous workers have outlined the variables that may affect the geotechnical properties of glacial deposits (e.g. Yatsu 1966; Terzaghi and Peck 1967; McGown 1971; Cabrera and Smalley 1973; Boulton and Paul 1976). Boulton (1976a, p.296) has perhaps best summed up the most important factors, suggesting that " . . . it is the processes of erosion and comminution during transport which are responsible for the particle-size distribution in tills. Mineralogy of the parent rock is also fundamentally important in determining the comminuted rate of eroded debris and relative proportions of the clay-size fraction composed of clay minerals and of rock flour. These parameters govern the position of any assemblage on the plasticity chart and therefore largely determine the fundamental geotechnical properties of the debris assemblages that go to form till".

Although the influence of particle-size and the mineralogical composition of the clay-size fraction of the till matrix have been considered at some length in Chapter 8, the results presented here lend some support to the hypothesis regarding the composition of the

matrix of the tills in the Carsphairn area. The results obtained for the grey till samples are compared with those presented by Busbridge (1968) from tills analysed from the Glasgow area, by Anderson (1972) from western Scotland and from various englacial and undisturbed lodgement tills by Boulton and Paul (1976) (termed the "T-line") in Figure 9.1. It is apparent that the values obtained for the grey till straddle the lower end of the "T-line", but fall away from the fields defined by Busbridge and Anderson. Their position seems somewhat anomalous, especially with reference to the relatively high percentages of clay-size material in the deposits. Normally, a clay-rich deposit defined by particle-size should possess a fairly high plasticity index if the particles less than 9ϕ in diameter comprise clay mineral silicates (Cabrera and Smalley 1973). Moreover, Boulton and Paul (1976, Figure 3) suggest that a till matrix with ca. 30 per cent clay should have a plasticity index approaching 20 per cent.

However, it may be possible to explain the low plasticity index yet high clay content if it is considered that much of the fine-grained material comprises crushed quartz and greywacke grains. This arrangement would tend to lower the plasticity index of the deposit because of the inactive short-range bonding forces associated with these particles (Terzaghi and Peck 1967; Cabrera and Smalley 1973; Boulton and Paul 1976). In addition, Smalley (1971) has suggested that in deposits where clay mineral silicates are involved the bond-weight ratio (R) is large; because the particles are small, powerful inter-particle forces are operating and as a result the deposit is cohesive. Alternatively, if the R value is low, the cohesion of the

deposit is low and its properties are determined by non-clay mineral particles, which usually comprise quartz particles; this latter condition apparently applies to the grey till deposits of the Carsphairn area.

Thus the results presented here and the arguments considered in Chapter 8 seem to support the conclusion that much of the matrix of the grey till deposits comprises rock flour rather than clay mineral silicates.

Further to the conclusions presented earlier regarding the particle-size analysis of the olive till, it is suggested that the absence of liquid limit and plastic limit phenomena in this till is due chiefly to two factors.

- 1) The dilution effect, by which increased percentages of coarser grained materials (possibly from the Cairnmore of Carsphairn granodiorite pluton) inhibit the development of Atterberg limits in the till, thereby giving the matrix a very low cohesion value and a high angle of internal friction.
- 2) The high percentages of quartz present in the till matrix, as shown by the lithological analysis, suggest that the short-range inactive bonding forces associated with these materials promote a reduction in the cohesive properties of the till.

9.4 SUMMARY AND CONCLUSIONS

Analysis of both tills from the Carsphairn area shows them to have low cohesive properties and possess high angles of internal

friction. The grey till matrix has a low plasticity index but a relatively high percentage of clay-size particles, while the olive till lacks Atterberg limit properties and has a concomitant high percentage of particles larger than 9 ϕ diameter. It is suggested that these properties are chiefly controlled by the lithology of the bedrock cropping out in the Carsphairn area and the mechanisms of subglacial crushing during transport and deposition of the debris that comprises the tills.

CHAPTER TEN
ROUNDNESS ANALYSIS OF TILLS
FROM THE CARSPHAIRN LANE -
WATER OF DEUGH - RIVER KEN AREA

10.1 INTRODUCTION

The roundness characteristics of both the olive and grey tills were determined on 102 samples (78 olive and 24 grey) from various exposures in the Carsphairn Lane - Water of Deugh - River Ken valley. The analysis was undertaken to test for any differences in roundness between the two tills, using the techniques described in Chapter 3. In addition, it was hoped that the results might enable inferences to be drawn regarding the mode and paths of glacial transport of the particles within each till as well as their environment of deposition, which in turn might throw light on the genesis of the cross-valley ridges. In the analysis, two different size fractions were examined for both olive and grey tills. The size fractions selected were:

- 1) 1.25 to 2.0 ϕ n = 60 (olive till = 48 samples; grey till = 12 samples).
- 2) -4.0 to -8.0 ϕ n = 42 (olive till = 30 samples; grey till = 12 samples).

The results and analysis of the two size fractions will be considered in Sections 10.2 and 10.3 respectively; the results of the entire data set are tabulated in Appendix II.

10.2 RESULTS AND ANALYSIS OF THE ROUNDNESS CHARACTERISTICS OF THE 1.25 TO 2.0 ϕ SIZE FRACTION

A total of 100 grains from each of 60 samples retained on the 0.25 mm sieve (1.25 to 2.0 ϕ), which corresponds to the "medium sand" particle-size devised by Wentworth (1922b), was examined under the microscope using the Powers (1953) visual comparison chart. The tills were sub-divided in the following manner.

- 1) Olive till (n = 48): sampled from the same landforms and sites as those described and listed in Chapter 8, Section 8.1.
- 2) Grey till (n = 12): the same as those listed in Chapter 8, Section 8.1, but less the one sample from the valley-fill deposit in the Water of Deugh valley.

Summary statistics for the roundness characteristics of the two tills are shown in Table 10.1. Sub-dividing the olive tills into the various landform types from which they were recovered, analysis of those from the cross-valley ridges alone shows their mean roundness value in each class to be: VA* = 31.4%, A = 50.6%, SA = 15.5%, SR = 2.1%, R = 0.4%. Olive till samples from the valley-fill deposits are very similar, being: VA = 31.5%, A = 52.5%, SA = 15%, SR = 0.9%, R = 0.1%. Of the 3700 particles examined no well rounded grains were recorded. The close relationship between the two data sets again

* Abbreviations to the Powers (1953) roundness classification:

VA = very angular; A = angular; SA = sub-angular; SR = sub-rounded; R = rounded; WR = well rounded.

confirms the observations made in Chapters 7 and 8 regarding the genetic link between the two landforms. Similar roundness properties are also exhibited by the inter-ridge till samples (Table 10.1). Since the tills are so closely related, the statistical analyses presented in this chapter combine the three landform types under the umbrella term of olive till. By comparison, the grey till samples show mean roundness values in each class of: VA = 20.7%, A = 49.9%, SA = 27.7%, SR = 1.7%, the main differences being a reduction in the percentage of very angular particles (by ca. 10%) and a corresponding increase in the sub-angular class of ca. 12%.

As a first step, the results of this analysis were plotted on a ternary diagram that included all six of the Powers (1953) roundness classes, grouped as VA/A; SA/SR; and R/WR. However, the very high percentages of VA/A grains (80 - 90%) and the very low frequency of R/WR particles (1 - 2%) made the diagram of little value. Since the latter group (as well as the sub-rounded class) provides an insignificant percentage of the total, the diagram was redrawn using only three of the roundness classes (viz: VA, A and SA), in the hope that any differences would be made clearer. Figure 10.1 depicts the redrawn diagram and shows the variation in roundness characteristics between the olive and grey tills (samples of drumlinoid and drumlin till are plotted in different ornament, see below). Under the generalised grouping of olive tills, it can be seen that they contain more very angular grains (20 - 40%), whereas the grey shows a greater proportion of sub-angular grains (25 - 40%). Angular particles appear evenly distributed between the two tills, comprising between 40% and 60% of the total.

Figure 10.1 Ternary diagram showing the results of the roundness analysis of the tills (1.25 to 2.0 ϕ size fraction) from the Carsphairn Lane - Water of Deugh - River Ken area.

Roundness analysis : 1.25 to 2.0 ϕ size fraction

△ Olive till n = 39

○ Drumlin till n = 4

■ Drumlinoid till n = 5

▲ Grey till n = 12

★ Mean of olive till

⊗ Mean of grey till

○ 95% confidence limits for olive and grey tills

⬡ $\pm 2\sigma$ of the mean value for olive and grey tills

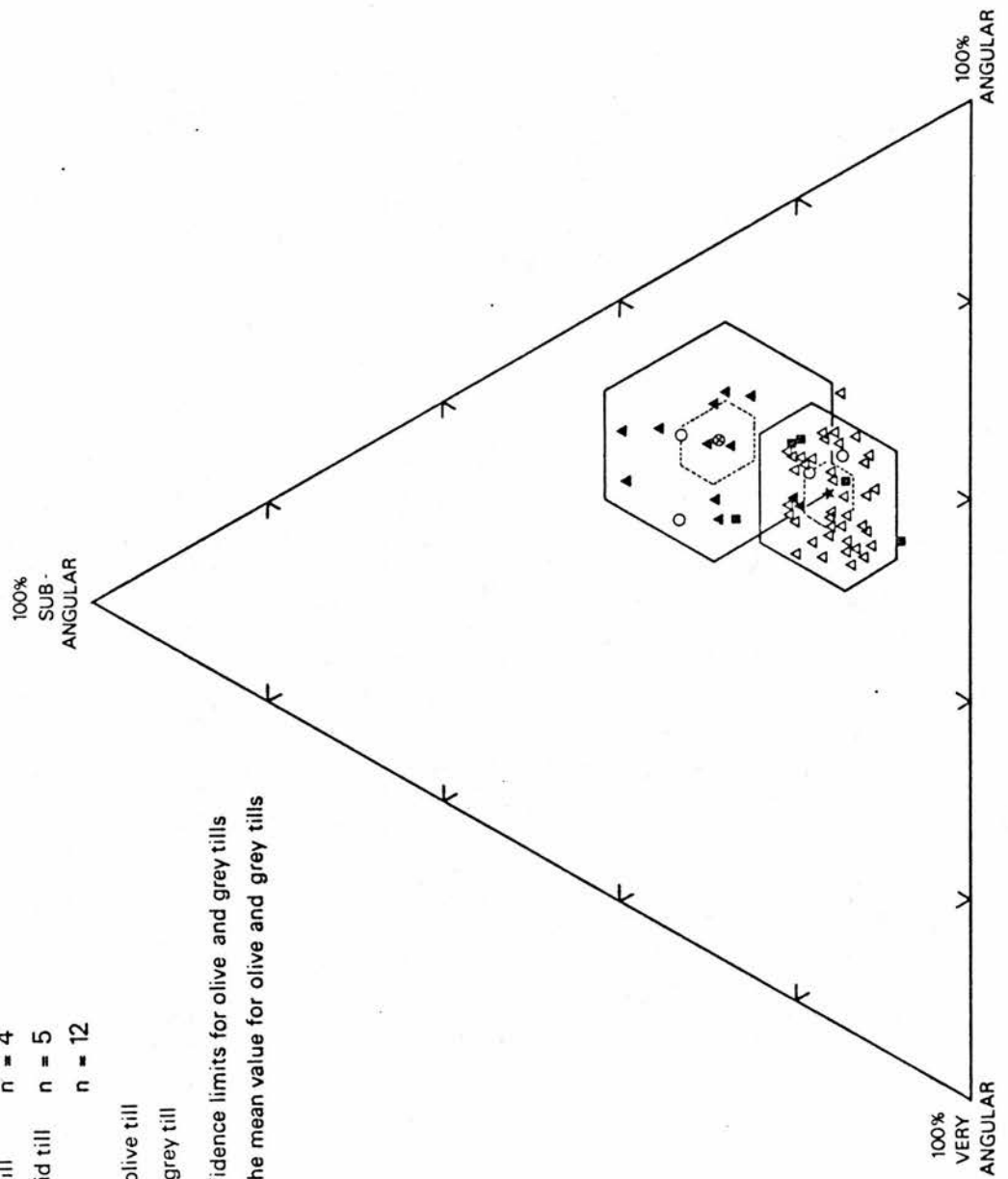


Table 10.1 Summary statistics of the roundness properties of tills
sampled from the Carsphairn Lane - Water of Deugh -
River Ken valley: 1.25 to 2.0 ϕ size fraction.

		*VA	A	SA	SR	R	WR
olive till (n = 29)	\bar{x}	31.4%	50.6%	15.5%	2.1%	0.4%	-
	σ	4.86	4.39	2.48	0.92	0.26	-
(cross-valley ridges)	V%	15.4	8.4	16.5	43.8	50.0	-
olive till (n = 8)	\bar{x}	31.5%	52.2%	15.0%	0.9%	0.1%	-
	σ	4.98	4.3	3.96	1.64	0.74	-
(valley-fill)	V%	15.9	8.5	25.5	77.0	-	-
olive till (n = 2)	\bar{x}	34.0%	50.5%	14.0%	1.5%	-	-
	σ	1.4	3.5	2.8	0.7	-	-
(inter-ridge till)	V%	4.1	6.9	20.0	46.7	-	-
olive till (n = 4)	\bar{x}	24.5%	50.0%	23.75%	1.75%	-	-
	σ	5.19	6.68	9.18	0.96	-	-
(drumlins)	V%	21.2	13.4	38.6	54.8	-	-
olive till (n = 5)	\bar{x}	29.4%	52.4%	17.0%	1.2%	-	-
	σ	6.62	5.5	6.59	1.6	-	-
(drumlinoids)	V%	22.5	10.5	38.8	-	-	-
Grey till (n = 12)	\bar{x}	20.7%	49.4%	27.7%	1.7%	-	-
	σ	6.3	4.98	6.5	0.87	-	-
	V%	30.4	9.98	23.5	49.7	-	-

\bar{x} = mean

σ = standard deviation

V% = coefficient of variation

*VA = very angular

A = angular

SA = sub-angular

SR = sub-rounded

R = rounded

WR = well rounded

Although a difference between the two tills is apparent, there is a slight overlap. This is shown to effect when the 95 per cent confidence limits and the $\pm 2\sigma$ field are plotted around the grand mean roundness value for each till (Figure 10.1). All except one of the 39 samples from the olive till fall within 2σ of their grand mean, but 11 of the samples lie in the 2σ field of the grey till; in fact the grand mean value for the olive till lies in this field.

It is interesting to note that the differences and similarities between the roundness results for the drumlin and drumlinoid tills closely match those described in Chapter 8 (Section 8.2) regarding their particle-size properties. The drumlins that lie farther from the former ice-shed (those in the $\pm 2\sigma$ field for the grey till (Figure 10.1)) have more sub-angular particles than the drumlins and drumlinoids that lie close to the down-ice termination of the cross-valley ridges (all except one sample falling in the $\pm 2\sigma$ field for the olive till (Figure 10.1)); the latter's percentage of very angular and angular grains are correspondingly higher. The mean roundness value for each class in the drumlinoid till is VA = 29.4%, A = 52.4%, SA = 17.0%, SR = 1.2%, which again compares well with the results obtained from the valley-fill and cross-valley ridge till.

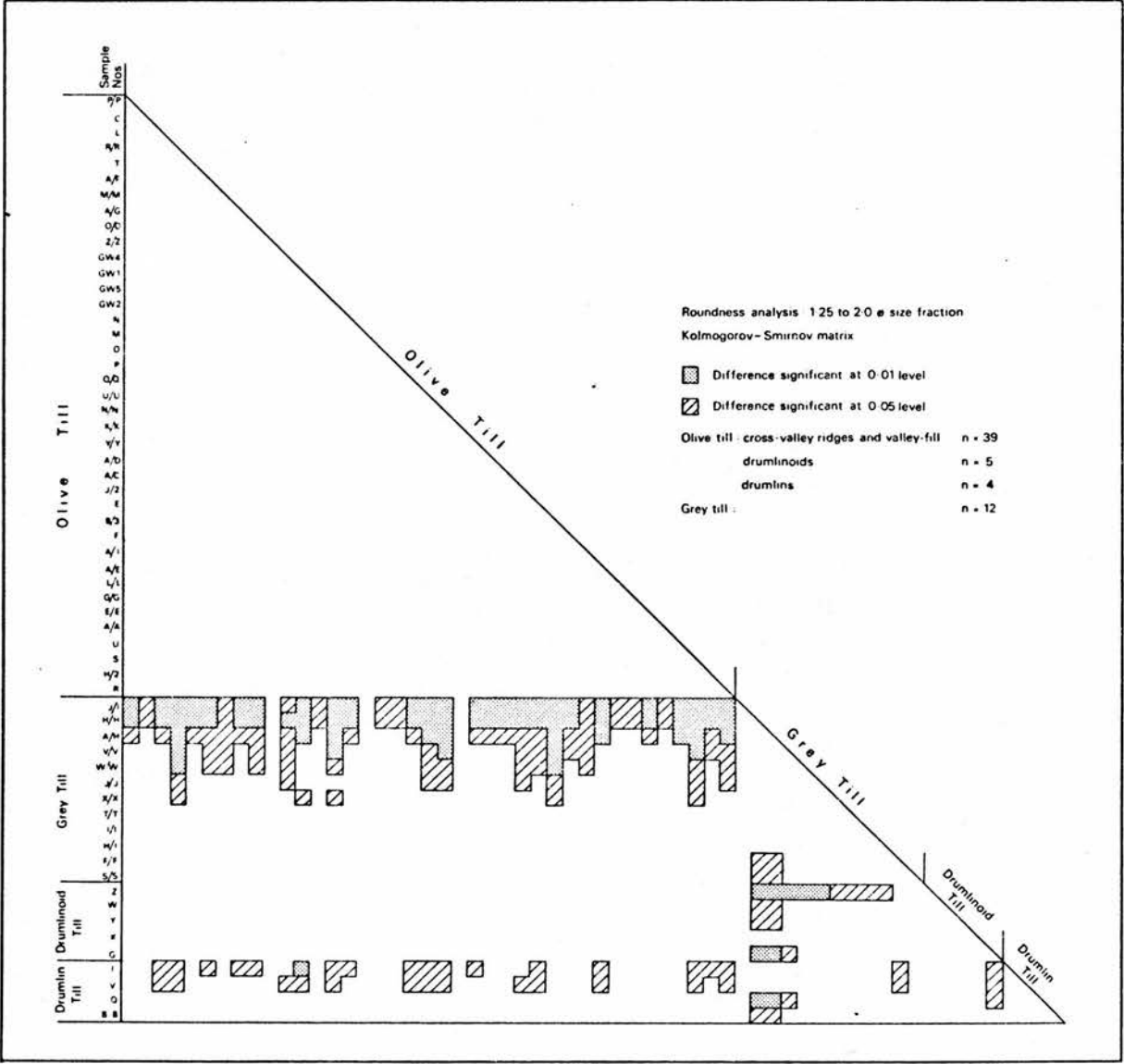
Various statistical techniques were employed to test whether the visual differences in roundness characteristics between the two tills are significant. First, the complete data set was analysed using the Kolmogorov-Smirnov test (Siegel 1956). This test is a non-parametric version of the t -test and is based on a comparison of two cumulative frequency curves. King and Buckley (1968), Gregory and Cullingford (1974) and Rose (1975) have previously used this technique

with a certain degree of success in attempting to determine whether depositional environments could be distinguished by differences in stone roundness. In the present study, the frequencies within each of the Powers roundness classes were compared and the maximum difference between any two classes noted and checked against the critical differences given by Miller and Kahn (1962). The samples were grouped into the following categories to facilitate overall comparisons:

olive till	: n = 39
grey till	: n = 12
drumlin till	: n = 4
drumlinoid till	: n = 5

The matrix of the results is presented in Figure 10.2. The pattern in the matrix reveals numerous unshaded squares, which represent samples that are not significantly different from each other. These are largely found within the olive till, indicating a high degree of uniformity within this type. However, six of the twelve samples from the grey till show no significance from the olive till in terms of roundness. These samples were recovered from various exposures distributed either within or marginal to the area defined by the cross-valley ridges, and no geographical or sedimentological correlations could be discerned for this similarity. In addition, a further three samples show no clear differences from the olive till; where a difference is present, it is invariably only significant at the 0.05 level. The remaining three samples are significantly different from the olive till, in some instances at the 0.05 level and in others at the 0.01 level. These results confirm

Figure 10.2 Kolmogorov-Smirnov test matrix comparing the results of the roundness analysis (1.25 to 2.0 ϕ size fraction) from olive till, grey till, drumlin till and drumlinoid till samples in the Carsphairn Lane - Water of Deugh - River Ken area. As the matrix is symmetrical only half is reproduced.



the degree of overlap between the olive and grey tills shown in Figure 10.1.

As a second step the mean roundness value for the whole of each sample was calculated. To ease the process of analysis the logarithmic rho (ρ) transform scale developed by Folk (1955) was employed. The limits of the class intervals are presented in Table 10.2, where they are compared with the classes defined by Powers (1953). Folk (1955) suggested that the results of roundness counts may be plotted as cumulative curves on arithmetic probability paper, the percentile measures read off and the graphic roundness parameters calculated (viz: mean roundness, standard deviation of roundness, roundness skewness, roundness kurtosis). However, all the results obtained in the study occur within only three or four of the six class intervals above. This gives a wide spread of points on the probability paper, which makes the shape of the curve less sensitive to graphic measures. Moreover, the class interval VA (or 0.0 to 1.0 ρ) invariably contained over 25 per cent of the particles counted. Thus in order to read off the lower percentile values required for the calculation of the graphic measures, the cumulative curve had to be extrapolated, an exercise that can lead to inaccurate results. It was therefore considered more appropriate to use statistical moment measures (Krumbein 1938; Friedman 1961, 1962), as these take into account every value within each class, whereas the equation used by Folk (1955) makes use of only two percentile readings from the plotted curve.

Before proceeding with this analysis, all samples were drawn as frequency curves in order to examine the distributions for

Table 10.2 Equivalence of the roundness class intervals of Powers (1953) and Folk (1955). (After Folk 1955).

Powers (1953) Visual roundness classes	Folk (1955) Rho scale class intervals
very angular	0.0 - 1.0
angular	1.0 - 2.0
sub-angular	2.0 - 3.0
sub-rounded	3.0 - 4.0
rounded	4.0 - 5.0
well rounded	5.0 - 6.0

bimodality. In all cases the distributions were found to be unimodal, although with a slight positive skew, and as such suited to analysis by statistical moment measures. The rho moment mean (the first moment) and the rho standard deviation (the second moment) were calculated using the following equations:

$$\bar{x}_p = \frac{\sum fd}{100} + d_o \quad (1)$$

$$\sigma_p = \sqrt{\left[\frac{\sum fd^2}{100} - \left(\frac{\sum fd}{100} \right)^2 \right]} \quad (2)$$

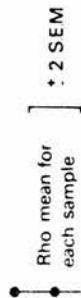
where fd is the product of the frequency (f) within each class and the difference (d) of that class from the assumed mean, while d_o refers to the mid-point of the class that contains the assumed mean of the sample. Computation of the third and fourth moment parameters was not attempted on the roundness data in this study, as Drake (1968) has shown that the results are generally inconclusive and often confusing.

The results of this analysis are shown in Figure 10.3, with the confidence limits for each sample represented by ± 2 standard errors from the mean; the group rho mean and its 95 per cent confidence limits are also plotted. The diagram shows that the rho mean roundness values and the respective confidence limits for all samples fall within the "angular" class of Powers (1953). Within this class interval there is a fairly clear distinction between the roundness characteristics of the olive and grey tills, although overlap is observable in a number of samples. The group mean roundness value of the grey till lies just outside the field enclosing the 95 per cent confidence limits of the olive till, while the reverse is true of the group mean value of the olive till. These results suggest that although a certain differentiation exists, there is a grading in terms of the roundness characteristics from one till into the other. A similar continuum is also seen in the results for samples from the drumlin and drumlinoid landforms, but the small sample sizes involved here lessen the significance of this observation.

The results in Figure 10.3 are arranged in a "random" manner so that any gross differences between the roundness properties of the tills may be seen objectively. To judge whether a spatial relationship exists between and within till types, the results were redrawn in terms of their respective positions from the former ice-shed zone in the Cairnsgarroch - Craig of Knockgray area (as defined by glacial erratics, ice-moulded landforms and striae described in Chapter 5), and parallel to the direction of ice movement. These results are presented in Figure 10.4, but the grey till

Figure 10.3 Results of the rho mean ± 2 S.E. calculations of
the roundness properties of the tills (1.25 to
2.0 ϕ size fraction) from the Carsphairn Lane
- Water of Deugh - River Ken area.

Roundness analysis :1.25 to 2.0 ø size fraction



OLIVE TILL (cross-valley ridges, valley-fill)

n=39

Sample numbers: L GW4 GW5 NN C RP R Z Z A/D A/G A/F N Y Y Q/Q B/3 X/K R U A/E G/G A/A S

GREY TILL

n=12

V/V J/J H/H T/T X/X W/I S/S W/W F/F J/J A/H I/I

OLIVE TILL Drumlins n=4

I V B/B Q

OLIVE TILL Drumlinoïds n=5

G K Z W Y

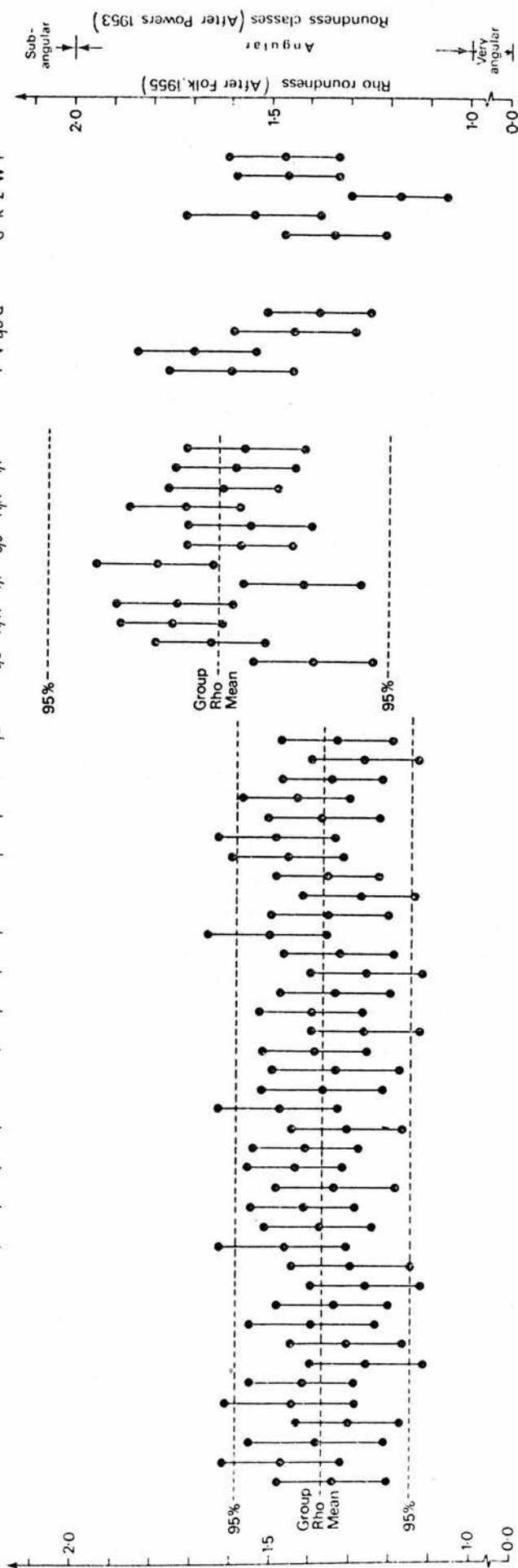


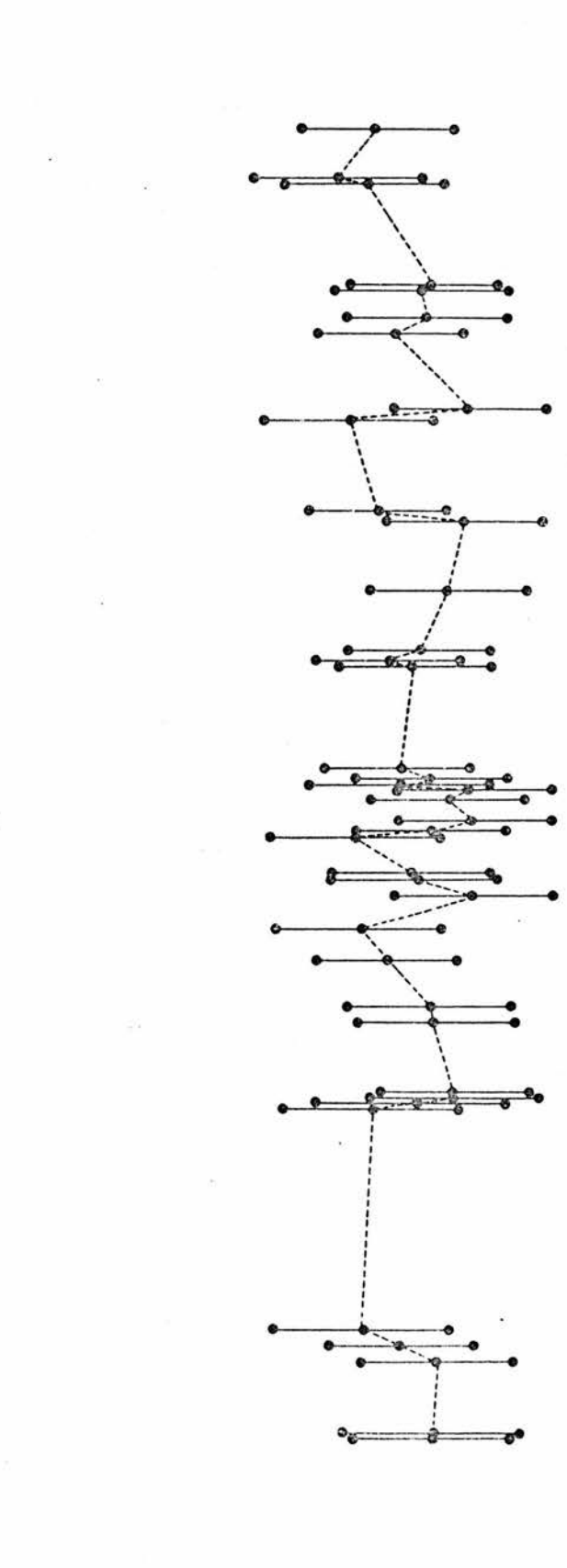
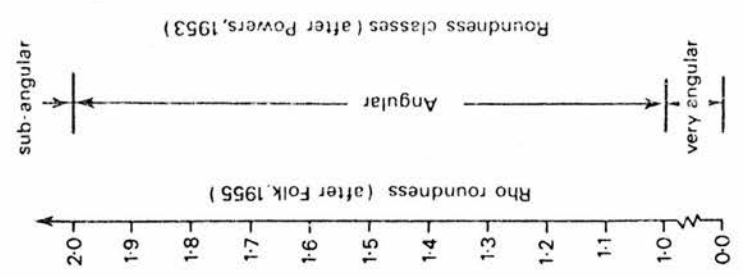
Figure 10.4 Results of the rho mean ± 2 S.E. calculations of the roundness properties (1.25 to 2.0 ϕ size fraction) of the olive till plotted against distance from the former ice-shed zone in the Carsphairn area.

Roundness analysis : 1.25 to 2.0 ϕ size fraction (olive till)

Rho mean for each sample
 $\pm 2 \text{ S.E.M.}$

Ice-shed zone

Km NW from ice-shed parallel to direction of former ice flow Km SE from ice-shed parallel to direction of former ice flow



samples have been omitted since their small number precludes spatial correlation. The olive till samples show an irregular pattern in terms of roundness in both a NW and SE direction from the former ice-shed, and no trend towards sub-angularity is apparent.

As a final step in the analysis the Mann-Whitney U test (large sample variant) was employed (Siegal 1958) to determine whether the mean roundness values of each sample had been drawn from the same population. The test is non-parametric, has a power efficiency of 95.5 per cent, and is a useful alternative to the t-test in that it does not contain the restrictive assumptions of the latter. For large sample sizes, the test is defined by the following equation:

$$Z = \frac{\left(\frac{n_1 n_2}{2} + \frac{n_1(n_1 + 1)}{2} - R_1 \right) - \frac{n_1 n_2}{2}}{\sqrt{\left(\frac{n_1 n_2}{N(N-1)} \right) \left(\frac{N^3 - N}{12} - \sum T \right)}} \quad (3)$$

where: n_1 = the number of olive till samples;
 n_2 = the number of grey till samples;
 N = total number of samples;
 R_1 = sum of the ranks given to the mean values in n_1 ;
 $\sum T$ = sum of the T values over all groups of tied ranks. (T is calculated from $\frac{t^3 - t}{12}$, when t is the number of observations tied for a given rank).

The Z score is used to establish the probability of an occurrence as an alternative to the U value because of the large size of the sample being analysed (Zar 1974). The null hypothesis was set up stating that there was no statistically significant difference between the rho

mean roundness properties of the two tills. The results of the analysis show that at the 0.01 level of significance the null hypothesis is rejected, indicating a statistically significant difference between the olive and grey till mean roundness characteristics in the 1.25 to 2.0 ϕ size fraction.

10.3 RESULTS AND ANALYSIS OF THE ROUNDNESS CHARACTERISTICS OF THE -4.0 TO -8.0 ϕ SIZE FRACTION

A similar programme of analysis was undertaken on the roundness characteristics of the -4 to -8 ϕ (16 mm to 256 mm) size clasts (corresponding to the "pebble" to "cobble" size fraction devised by Wentworth 1922b) measured at various exposures in the olive and grey tills in the Carsphairn Lane - Water of Deugh - River Ken valley. At each of the 42 sites sampled 100 clasts were compared with a set of photographs of clay models representing varying degrees of roundness and the clasts allocated to one of the six classes defined by Powers (1953). The samples were recovered from the following landforms.

- 1) olive till (n = 30): eight from valley-fill deposits, two from inter-ridge areas and 20 from cross-valley ridges.
- 2) grey till (n = 12): the same as those listed in Chapter 8, Section 8.1, but less one of the samples from the basal part of one of the cross-valley ridges in the Carsphairn Lane valley.

Summary statistics for the roundness characteristics of the two tills are presented in Table 10.3. The mean roundness values for the olive till from valley-fill, inter-ridge and cross-valley ridge landforms are almost identical and compare closely with the results analysed in Section 10.2. Samples from the grey till show an increased number of sub-angular clasts by ca. 12 per cent and the very angular and angular clasts correspondingly reduced by ca. 7 per cent and ca. 2 per cent respectively.

As with the analysis of the 1.25 to 2.0 ϕ particles, a high percentage of very angular and angular clasts was recorded. After redrawing of the ternary diagram using only three roundness classes (see Section 10.2) a fairly clear separation between the two tills is observable (Figure 10.5). The 95 per cent confidence limits and the intervals of $\pm 2\sigma$ from the mean roundness value suggest a certain overlap between the two tills. This, however, may be misleading, for the wide dispersion of the small number of grey till samples produces a large standard deviation, which in turn encompasses a substantial field on the ternary diagram. In an attempt to assess whether the degree of overlap was significant, the complete data set was analysed using the Kolmogorov-Smirnov test and the results are presented in matrix form in Figure 10.6. The samples are separated into two major groups:

olive till : n = 30

grey till : n = 12.

It is apparent from Figure 10.6 that only three of the 12 grey till samples are consistently significantly different from the olive till samples. For six of the remainder no clear pattern of difference

Figure 10.5 Ternary diagram showing the results of the roundness analysis of the tills (-4 to -8 ϕ size fraction) from the Carsphairn Lane - Water of Deugh - River Ken area.

Roundness analysis : -8.0 to -4.0 size fraction

△ Olive till (n = 30)
▲ Grey till (n = 12)
★ Mean of olive till
⊗ Mean of grey till
○ 95% confidence limits for olive and grey till
○ ±2σ of the mean value for olive and grey till

100% SUB-ANGULAR

100% VERY ANGULAR

100% ANGULAR

Roundness analysis : -8.0 to -4.0 size fraction

△ Olive till (n = 30)
▲ Grey till (n = 12)
★ Mean of olive till
⊗ Mean of grey till
○ 95% confidence limits for olive and grey till
○ ± 2σ of the mean value for olive and grey till

100% SUB-ANGULAR

100% VERY ANGULAR

100% ANGULAR

Roundness analysis : -8.0 to -4.0 size fraction

△ Olive till (n = 30)
▲ Grey till (n = 12)
★ Mean of olive till
⊗ Mean of grey till
○ 95% confidence limits for olive and grey till
⊖ ±2σ of the mean value for olive and grey till

100% SUB-ANGULAR

100% VERY ANGULAR

100% ANGULAR

Roundness analysis : -8.0 to -4.0 size fraction

△ Olive till (n = 30)
▲ Grey till (n = 12)
★ Mean of olive till
⊗ Mean of grey till
○ 95% confidence limits for olive and grey till
○ ±2σ of the mean value for olive and grey till

100% SUB-ANGULAR

100% VERY ANGULAR

100% ANGULAR

Roundness analysis : -8.0 to -4.0 size fraction

△ Olive till (n = 30)
▲ Grey till (n = 12)
★ Mean of olive till
⊗ Mean of grey till
○ 95% confidence limits for olive and grey till
⊖ ±2σ of the mean value for olive and grey till

100% SUB-ANGULAR

100% VERY ANGULAR

100% ANGULAR

Roundness analysis : -8.0 to -4.0 size fraction

△ Olive till (n = 30)
▲ Grey till (n = 12)
★ Mean of olive till
⊗ Mean of grey till
○ 95% confidence limits for olive and grey till
⊖ ±2σ of the mean value for olive and grey till

100% SUB-ANGULAR

100% VERY ANGULAR

100% ANGULAR

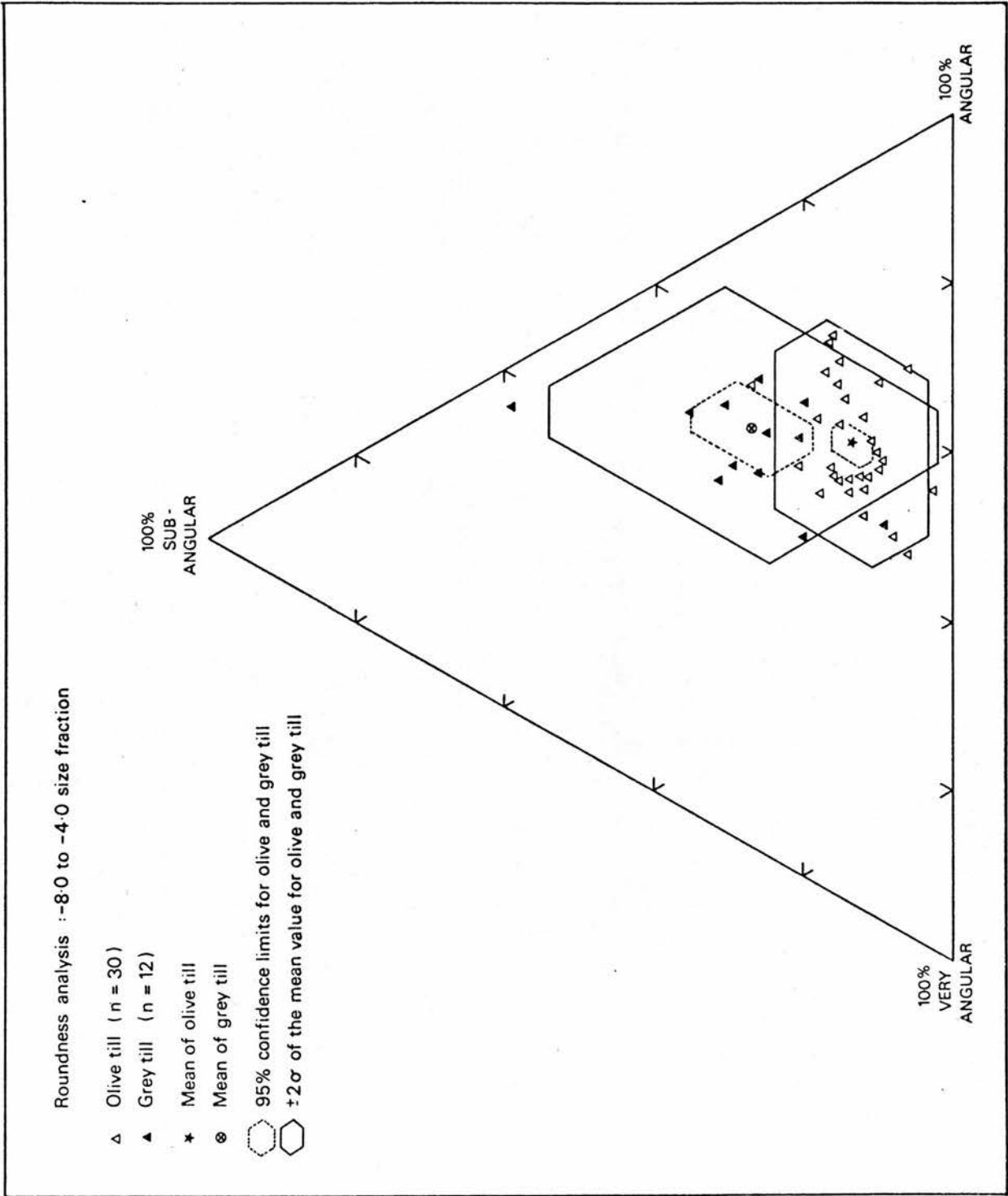


Figure 10.6 Kolmogorov-Smirnov test matrix comparing the results of the roundness analysis (-4 to -8 ϕ size fraction) from olive and grey till samples in the Carsphairn Lane - Water of Deugh - River Ken area. As the matrix is symmetrical only half is reproduced.

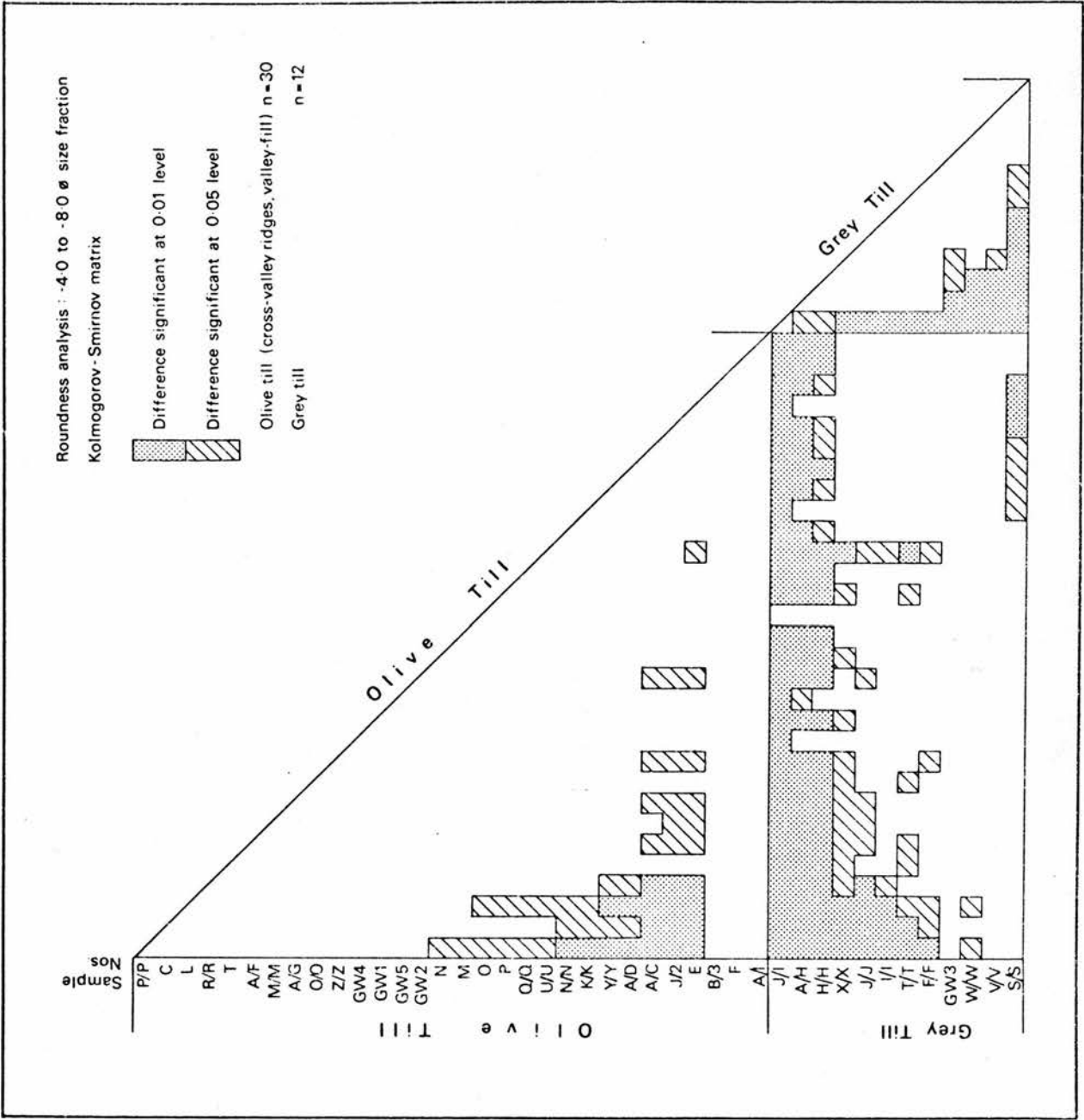


Table 10.3 Summary statistics of the roundness properties of tills sampled from the Carsphairn Lane - Water of Deugh - River Ken valley: -4.0 to -8.0 ϕ size fraction.

		VA	A	SA	SR	R	WR
olive till (n = 20)	\bar{x}	32.05%	55.6%	11.1%	1.14%	0.1%	-
	σ	8.49	6.56	4.23	1.23	0.45	-
(cross-valley ridges)	V%	26.5	11.7	38.1	-	-	-
olive till (n = 8)	\bar{x}	31.5%	52.75%	13.88%	1.62%	0.25%	-
	σ	5.1	5.73	3.76	1.77	0.71	-
(valley-fill)	V%	16.2	10.9	26.9	-	-	-
olive till (n = 2)	\bar{x}	32.0%	50.0%	16.0%	1.5%	0.5%	-
	σ	19.8	5.66	12.7	0.71	0.71	-
(inter-ridge till)	V%	61.9	11.3	79.4	47.3	-	-
grey till (n = 8)	\bar{x}	24.3%	49.0%	25.4%	1.3%	-	-
	σ	10.49	6.7	13.9	1.36	-	-
	V%	43.2	13.7	54.7	-	-	-

emerges, while the final three samples show a closer affinity to the roundness properties of the olive till than to the grey; they show a significant difference from four of the other grey ones at the 0.01 and 0.05 levels. To complicate the picture, significant differences also occur within the olive till samples themselves (Figure 10.6).

The variations outlined above suggest that the difference in roundness between and within the two tills are more complex than the results of the analysis in Section 10.2 would indicate. Moreover, the differences between various samples show no specific geographical correlations, being spread in a random manner over the area within

which the cross-valley ridges are located.

The rho moment mean (with 95 per cent confidence limits) and rho standard deviation were calculated for all samples using the procedure outlined in Section 10.2. The results are shown in Figure 10.7, where the samples are plotted in a "random" manner, the only separation being into olive and grey categories. The results compare favourably with those obtained from roundness analysis of the 1.25 to 2.0 ϕ size fraction in that all, except one, of the 42 samples fall within the "angular" class as defined by Powers (1953). Again there is a slight overlap between the tills in terms of the rho mean roundness value calculated for each sample. Interestingly, the group rho mean roundness value for the grey till falls within two standard errors of the mean for the olive till, while the same is also true in the reverse case.

When the rho mean roundness values for each of the olive till samples are plotted against distance from the former ice-shed, no pattern of any kind is observable (Figure 10.8). The rapid increase in the roundness of clasts, towards sub-angularity, in basal till as discussed by Krumbein (1941b) and Drake (1972) is not confirmed. This indicates that the processes of glacial rounding were inhibited and that this may have been due either to the position of the clasts during transport, being above the zone of traction at the base of the ice, or that transport of the clasts was of limited extent. These possibilities are considered in more detail in Section 10.4.

Finally, the rho mean roundness values for the grey and olive tills were compared statistically using the Mann-Whitney U-test (see Section 10.2). The null hypothesis stating that there was no

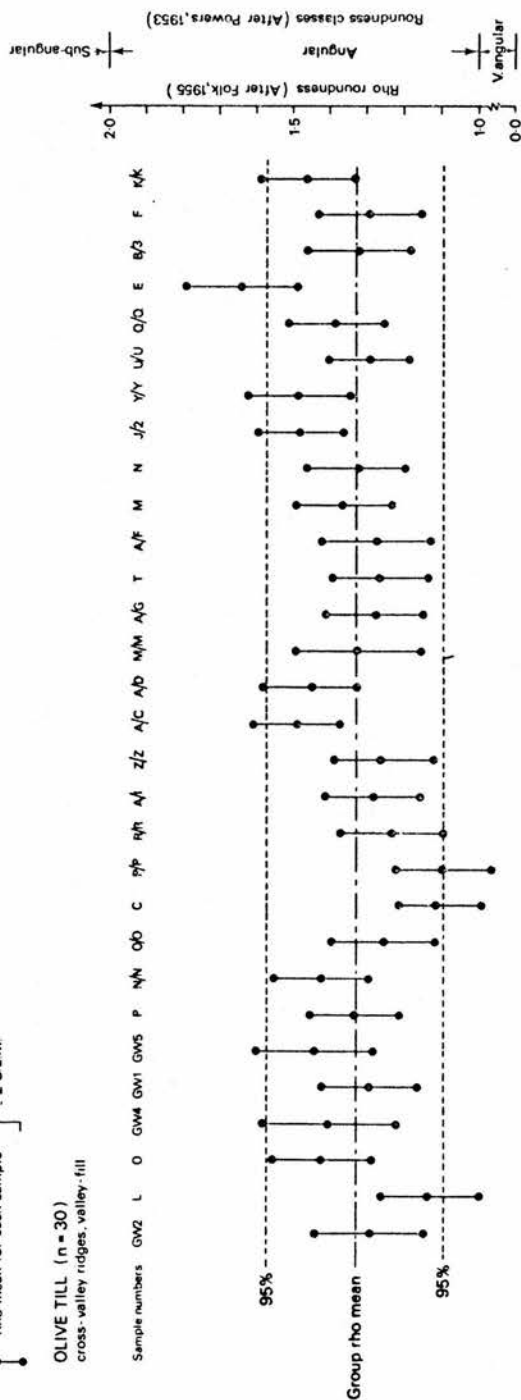
Figure 10.7 Results of the rho mean ± 2 S.E. calculations of
the roundness properties of the tills (-4 to
-8 ϕ size fraction) from the Carsphairn Lane -
Water of Deugh - River Ken area.

Roundness analysis : -8.0 to -4.0 ϕ size fraction

Rho mean for each sample ± 2 S.E.M.

OLIVE TILL (n = 30)
cross-valley ridges, valley-fill

Sample numbers GW2 L O GW4 GW1 GW5 P N/N Q/D C W/P W/M A/I Z/I A/C A/D M/M A/G T A/F M N J/2 V/Y U/U Q/D E B/D F K/K



GREY TILL (n = 12)
Sample numbers S/S V/V W/W J/I F/F W/H J/U V/T A/H X/X I/H G/W

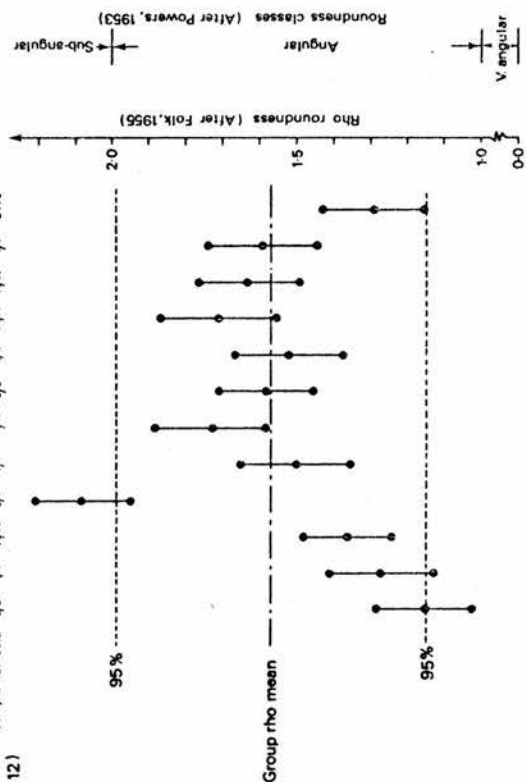
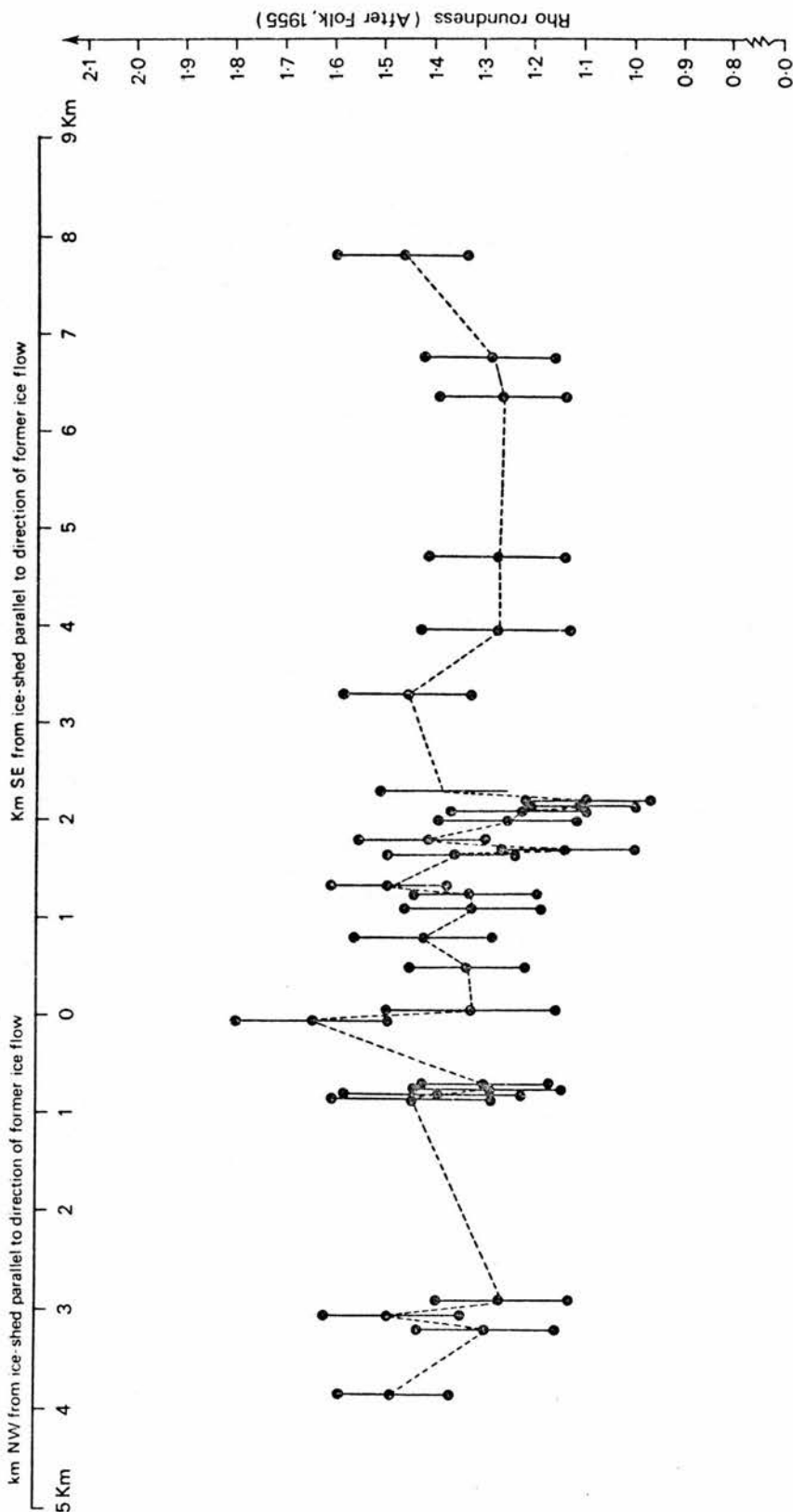


Figure 10.8 Results of the rho mean ± 2 S.E. calculations of the roundness properties (-4 to -8 ϕ size fraction) of the olive till plotted against distance from the former ice-shed zone in the Carsphairn area.

Roundness analysis: -4.0 to -8.0 ϕ size fraction (olive till)

Rho mean for each sample $\pm 2 \text{ SEM}$

ice-shed zone



significant difference between the mean roundness of the two tills was rejected at the 0.01 level.

10.4 DISCUSSION OF THE ROUNDNESS ANALYSIS RESULTS

The majority of the analyses carried out on the roundness data collected for the two size fractions show a certain degree of differentiation between the grey and olive tills, although some overlap between the two is a consistent feature. The Kolmogorov-Smirnov tests and the plotting of the rho mean roundness values, for example, show that the relationship between the roundness characteristics of the two tills is not as clear as the results from the Mann-Whitney U-tests would suggest. Thus, the following discussion will attempt to evaluate this complex relationship in terms of the major factors that have been found, by various workers, to control the roundness characteristics of particles in till deposits. Further, although evidence from the roundness characteristics alone cannot be related unequivocally to differences in transportation and environment of deposition of the tills, certain general inferences can be made to this end and these will be considered in the latter part of this section.

Although little work has been carried out on the effect of size of particle on roundness within a glacial environment, roundness studies on beach and fluvial material show that different sizes respond in different ways to processes acting in the same environment. Wadell (1935), Russell and Taylor (1937), Pettijohn and Lundahl (1943) and Sneed and Folk (1958) demonstrated that large size material is better rounded than smaller grades in beach and fluvial

environments, while Sarmiento (1945) showed that in laboratory experiments larger fragments tend to round more rapidly than smaller sizes. Pettijohn (1957) further suggested that where materials of varying sizes have not been transported far, then all size grades have the same roundness. Although the processes of rounding acting beneath a glacier are obviously different from those operating in beach or fluvial environments, the fact that the roundness results for both the clasts and sand-size particles in the olive till are almost identical suggests that both have not been transported any great distance. This interpretation is also supported by the restricted distribution of Craig of Knockgray microgranite and Caradocian conglomerate erratics in the Carsphairn area (Chapter 5), which indicate that glacial transport of debris has been limited owing to the former existence of an ice-shed zone in the vicinity during the Late-Devensian glaciation.

Roundness may also be said to be partly related to the shape of the particle on leaving its bedrock source (Tester 1931; Pettijohn 1957; Drake 1970) as well as to distance of transport (Pettijohn 1957; Holmes 1960; Drake 1972; Bergerson 1973), but a noticeable characteristic of both the olive and grey tills is the angularity of the included clasts and particles. A total of 3000 clasts between -4.0 and -8.0ϕ in intermediate diameter in the olive till (all clasts analysed comprised "fresh" bedrock, weathered stones when encountered were discarded) was closely examined during analysis but not a single stone was found to be striated. Moreover, 86.2 per cent of the clasts showed little evidence of transport (VA to A class of Powers (1953)). The very occasional rounded or sub-rounded clast

(1.5%) that was encountered was invariably composed of milky quartz or granodiorite and could be referred to the disaggregation of the Caradocian conglomerate or the Cairnsmore of Carsphairn pluton. Similarly 1200 clasts from the grey till were scrutinised and only at one exposure (that by Lamloch House: NX 528965) were the clasts found to be striated. In addition the marked angular to sub-angular nature of the clasts is a prominent feature (74.4%), while the very angular clasts comprise 24.3% of the total (compared with 31.7% for the olive till); rounded and well rounded clasts are absent.

The dominant very angular to angular characteristic of the clasts in the olive till appears to be a feature of the greywacke rocks in this area. This is corroborated by empirical tests undertaken on a series of fresh, local bedrock samples that were compared with the till clasts. In these tests all the freshly broken bedrock fragments had a roundness value in the angular or very angular classes of Powers (1953). This indicates that the clasts contained in the olive till have undergone little rounding since their detachment from the bedrock, which again implies that they may not have been transported any great distance. This interpretation, however, does not completely explain the higher percentages of sub-angular clasts at the expense of very angular ones in the grey till, for the lithology of the clasts in both tills is almost exclusively greywacke. Thus the rounding process must have been operating, at least on the clasts in the grey till, which suggests that the position of transport within the ice or the environment of deposition of the debris may have also influenced the roundness properties of the clasts (see below).

In the same way 3900 particles, in the 1.25 to 2.0 ϕ size fraction, from the olive till (excluding the drumlin and drumlinoid samples) were examined. Of these 83.6 per cent showed very angular or angular characteristics, while only 15.1 per cent were sub-angular. Of the 1200 particles inspected from the grey till 20.7 per cent were very angular, 49.9 per cent were angular and 27.7 per cent sub-angular (1.7 per cent were sub-rounded). Again the angular nature of the particles is a prominent feature. Although the angularity is in part a function of the angular nature of the quartz particles and rock fragments contained in the greywacke bedrock itself (Chapter 2, Section 2.2) and the anhedral form of the quartz in the granodiorite, it does not entirely explain the differences in the percentage of very angular and sub-angular particles between the two tills. Since, as argued above, the till debris has not been transported very far, it is clear that processes must have been operating over this short distance that emphasised the differences in roundness characteristics between the tills.

Experimental work by Marshall (1927) on hard, uniform greywacke rocks showed that in a laboratory grinding mill cobbles, gravels and sand particles were reduced by 3.5 per cent of their weight by a combination of grinding (most important), impact and abrasion per mile travelled. Although the simulation of grinding and abrasion is not identical to comminution beneath glacier ice, Marshall's results are instructive in that they indicate the rapidity with which resistant greywacke rocks may be reduced, which in turn would be reflected in their roundness characteristics. This conflicts with the evidence presented above, where the clasts appear to have suffered

little comminution. Certain workers have also demonstrated that a rapid increase in the roundness of clasts occurs immediately (within ca. 2 - 3 km) down-ice of their entrainment in the glacier (e.g. Krumbein 1941b; Drake 1972; Gregory and Cullingford 1974; Reheis 1975). However, no such increase in roundness values for the clasts and sand-size particles in the olive till over the initial 2 - 3 km is observable (Figures 10.4 and 10.8). This suggests that the contained particles have not undergone the extensive crushing and abrasion required during transport to reach the sub-angular "equilibrium state" as defined by Drake (1972). This contention is supported by the overall negligible increase in the roundness values of the clasts and sand-size particles in the olive till up to 8 km to the SE from the former ice-shed in the Carsphairn area as shown in Table 10.4 (the lack of samples recovered to the NW precludes a similar analysis). In this table the percentage roundness values of clasts and sand-size particles per km are tabulated against distance down-ice from the former ice-shed and show a consistent symmetrical distribution about the angular roundness class. Similar results were recorded by Holmes (1960) in his study of till clasts from central New York. He concluded that degrees of roundness showed a gradual transition from "sharply angular" to "slightly rounded" and thus towards a "moderately rounded" condition. He found that over 90 per cent of the clasts occurred in the first two above-mentioned classes and that less than 0.5 per cent were in the "well-rounded" category. Holmes argued that this difference was due to the termination of the rounding process by crushing of the clast before it passed the "slightly rounded" stage. Vagners (1966) also

Table 10.4 Olive till roundness results (1.25 to 2.0 ϕ and -4.0 to -8.0 ϕ size fractions) tabulated against distance from the former ice-shed zones in the Carsphairn area.

[illegible]

olive till roundness v. distance from former ice-shed (normalised for pebble numbers per km)

Number of pebbles	-4 to -8 ϕ size fraction								1.25 to 2.0 ϕ size fraction										
	300	700	400	200	100	-	200	100	300	700	400	200	400	200	100				
very angular	1.5	1.8	2.0	1.5	1.9		1.8	1.2	0.9	1.2	1.1	1.0	1.0	1.1	1.1	0.9	0.9		
angular	2.8	2.8	2.8	2.9	2.5		2.6	2.8	1.8	1.8	1.8	1.9	2.0	1.8	1.8	1.9	1.9		
sub-angular	0.6	0.6	0.4	0.5	0.6		0.6	0.1	0.6	0.5	0.5	0.2	0.5	0.6	0.5	0.7	0.6		
sub-rounded	0.1		0.1	0.2	0.1		0.1		0.1										
rounded																			
well rounded	0	1	2	3	4	5	6	7	8	0	1	2	3	4	5	6	7	8	9
→ km SE from former ice-shed										→ km SE from former ice-shed									

found a similar pattern with the roundness values of glacially transported dolostone rock in southern Ontario, Canada: dolostone tended to be crushed so that a rounding of only 0.2 ± 0.5 , in the Krumbein (1941a) classification (approximating to the angular class of Powers (1953)), was maintained.

The observations of Holmes (1960) and Vagners (1966) were made at sites between 0 and 24 km and 0 and 50 km from their respective bedrock sources, and demonstrate that over considerable distances only limited rounding of till debris may occur. However, in the Carsphairn area, it has been shown that only limited glacial transport of the till occurred. The apparent paradox between rapid rounding over short distances (Drake 1972), limited rounding over long distances (Holmes 1960; Vagners 1966) and limited rounding over short distances (this study) may be partly explained by considering the position at which the debris was transported in the ice.

Gry (1974), working in Scandinavia, found that basalt and porphyry debris was rapidly crushed to a size determined by the jointing of the rocks and thereafter transported in the ice without further crushing. He suggested that the material had been conveyed to a position above the zone of traction at the glacier base, where crushing and abrading mechanisms were less intensive. Similarly, Boulton (1978) considered that clast shape was dependent on the transport path of the debris in the ice. Debris transported supra-glacially and at high englacial positions in Breidamerkurjökull (Iceland) and Søre Buchanansisen (Spitzbergen) glaciers were shown to be angular (ca. 0.2 on Krumbein's (1941a) scale), while debris that had come into contact with the glacier bed in the same two

glaciers was more rounded (0.6 to 0.8 on Krumbein's (1941a) scale).

Boulton (1978) also defined two sub-zones in the subglacial transport path:

- (a) the sub-zone of traction in ^{which} individual particles although held in the ice are in contact with the bed and are therefore retarded; and
- (b) the sub-zone of suspension in ^{which} particles are contained entirely within, and move with the same velocity as, the ice.

He suggested that owing to the complex flow patterns that occur in the basal ice zone movement of particles from one sub-zone to the other may occur, and thus defined the basal transport zone as "one in which particles are or have been at some time in the basal zone of traction" (Boulton 1978, p.778).

The observations of Gry (1974) and Boulton (1978) are important, for they demonstrate how roundness may be affected by the position of debris during glacier transport. This has implications for the evolution of the roundness characteristics of the clasts and sand-size particles in the tills of the Carsphairn area as well as for the origins of the cross-valley ridges and these are discussed below.

From the above discussion there are three possibilities regarding the relationship between the two tills in the Carsphairn area, their roundness characteristics, and their mode of glacial transport.

- 1) The clasts in the olive till may have undergone mechanical frost shattering, or similar breakage caused by precipitation of salts along fractures, in a supraglacial environment, thus

producing a suite of dominantly angular clasts and removing any striae (cf. Upham 1881; Sharp 1949; Elson 1961; Drake 1971; Flint 1971), while the grey till was deposited as a subglacial lodgement deposit. This suggestion, however, does not accord with the evidence presented in Chapters 7 and 8 regarding the indurated nature of the olive till, the absence of any inter-bedded sedimentary deposits, the relatively high silt content and the virtual exclusion of any rounded clasts (produced by localised transport in supraglacial meltwater streams). These features are well documented as being characteristic of till that has undergone transport in the lower layers of glacier ice and deposited either as basal melt-out or lodgement till (cf. Drake 1971; Goldthwait 1971; Francis 1975; Boulton 1976c; Dreimanis 1976). Moreover, the similarity in the particle-size and roundness properties of the olive till comprising the valley-fill, cross-valley ridge and drumlinoid landforms as well as their close morphological association suggests a subglacial origin for the deposits rather than a supraglacial one.

- 2) The debris comprising the olive till was transported at the base of the ice and the equilibrium form of this material is angular; the clasts passing through a series of cycles by which they were repeatedly crushed to an angular (or very angular) shape before any increase in the roundness characteristics could have been imparted to them. However, if this were so, then it should be expected that the clasts in the grey till would follow a similar pattern, since the lithology

of the clasts in both tills is predominantly greywacke, and as such produce little or no differences between the roundness of the two tills; this latter observation has been shown not to be the case.

- 3) The olive till debris was transported in the ice at low levels (i.e. a low englacial position), but generally above the basal zone of traction. The absence of very high contact pressures in the former zone would tend to reduce the amount of rounding and thus help maintain the angular to very angular nature of the entrained particles (cf. Goldthwait 1971; Dreimanis 1976; Boulton 1978). In addition, the sub-angular to angular nature of the grey till debris may be explained by transportation within the basal zone of crushing and abrasion in the ice. The absence of any clear separation in the roundness properties between the two tills may also be accounted for, since the limited distance of transport would have precluded the development of two distinct suites of particle and clast roundness.

It is therefore suggested that the third hypothesis is the most reasonable in terms of explaining the differences between the roundness characteristics of the two tills in the Carsphairn area, as it is supported by the evidence presented above as well as by that from morphological observations and the particle-size analysis.

Finally, it was suggested in Chapter 8 (Section 8.3) that the high percentage of silt-size material in the olive till may have been a product, in part, of interparticle crushing during deposition of the till. If this were so then the angular nature of the clasts in

the olive till might also be a response to this mechanism.

10.5 SUMMARY AND CONCLUSIONS

It has been argued above that the roundness characteristics of the clasts and particles in the two tills from the Carsphairn area have been controlled by three main factors.

- 1) The very angular nature of the debris when initially eroded from its bedrock source has persisted in the till.
- 2) The evidence presented from the distribution of glacial erratics in the Carsphairn area shows that the coarse fraction of the olive till is of a local character. Thus it is concluded that the short distance of glacial transport has helped reduce the amount of rounding of this material; this also partly explains the high percentages of angular clasts and sand-size particles in both tills.
- 3) The difference in the roundness properties of the two tills may be explained by differences in the position of the debris comprising each deposit during transportation, viz:

olive till debris: low englacial position of transport,
less intensive comminution processes
therefore producing very angular to
angular particles.

grey till debris: basal position of transport, more
intensive comminution processes pro-
ducing angular to sub-angular
particles.

The similarity in roundness in both size fractions of the olive till from the valley-fill, cross-valley ridges and drumlinoids confirms the observations made on the particle-size and morphological association of these landforms and supports the view that they are genetically related.

CHAPTER ELEVEN

TILL MACRO-FABRIC ANALYSIS FROM
THE CROSS-VALLEY RIDGES IN THE
CARSPHAIRN AREA

11.1 INTRODUCTION

Till macro-fabric analysis has proved to be a useful tool in attempts to determine the origin of certain glacial landforms (e.g. Hoppe 1952; Cowan 1968; Walker 1973; Cullingford and Gregory 1978). Thus it was decided to employ this technique in support of the roundness and particle-size techniques, in the analysis of the cross-valley ridges by Carsphairn.

In attempting to analyse the data it was found that many of the statistical procedures yielded ambiguous results. This was particularly the case with till fabrics that were bimodally or multimodally distributed. It was therefore considered necessary to examine these techniques critically and in some detail in order to establish a clear methodology for the statistical analysis of the till fabric data collected in the study area. As a result this chapter comprises two major sections:

- 1) a critical examination of the statistical techniques* hitherto

* In discussing the statistical techniques employed in the analysis of till fabric data it was found necessary to use specific examples. In order to maintain continuity these examples have been drawn from the data collected by the present writer in the Carsphairn area. Thus a certain amount of duplication of the fabric diagrams has been unavoidable.

employed in the analysis of till fabric data and the provision of an alternative methodology for the analysis of such data; and

- 2) the presentation and discussion of the till fabric data collected from the cross-valley ridges.

11.2 A REVIEW OF THE STATISTICAL TECHNIQUES EMPLOYED IN TILL FABRIC ANALYSIS

11.2.1 Introduction

The analysis of till macro-fabrics may be defined as being the study of the orientation and dip of individual clasts within a till. Although some nineteenth century geologists noticed that pebbles in till seemed to possess a preferred trend (Hind 1859 *vide* Elson 1966; Miller 1884), the potential significance of these observations was not recognised until Richter (1932, 1933, 1936) provided a quantitative analysis of the relationship between pebble orientations in till and the direction of former ice movement. Holmes (1941) elaborated on this phenomenon, producing the most detailed study yet attempted on till fabrics.

Since that time till fabric analysis has become widely used by glacial geomorphologists to provide four main types of information:

- 1) The determination of former ice flow directions by the regional analysis of till fabrics; this has usually been based upon a one-sample, one-site sampling programme (e.g. West and Donner 1956; Kirby 1961, 1969; Saunders 1968; Beaumont 1971a; Drake 1971; Garnes 1973; Mickelson 1973).

- 2) The genesis of fabric properties and the mode of till deposition (e.g. Holmes 1941; Glen et al. 1957; Harrison 1957a; Penny and Catt 1967; Boulton 1968, 1971; Mark 1974; Marcussen 1975).
- 3) The genesis of glacial landforms composed of till, including drumlins (e.g. Wright 1957; Hill 1971; Walker 1973), "cross-valley" moraines (e.g. Andrews 1963a and b; Andrews and Smithson 1966), ribbed moraine (Cowan 1968) and hummocky moraine (Hoppe 1952; Cullingford and Gregory 1978).
- 4) The detailed analysis of a limited number of sections to provide information on till variability over short distances and to examine critically the validity of current sampling procedures and the inferences that may be drawn from till fabric analysis (e.g. Kauranne 1960; Andrews and Smith 1966, 1970; Andrews and King 1968; Harris 1969; Young 1969).

More recently, studies have also been focused on:

- (a) the influence of operator variance in the sampling of till fabrics (e.g. Hill 1968; Krüger 1973).
- (b) the influence of pebble shape on the form of till fabrics (e.g. Holmes 1941; Andrews and King 1968; Krüger 1970; Ramsden 1970; Drake 1974, 1977).

(i) Field procedure

The methods of collecting till fabric measurements in the field have been reviewed at length in Chapter 3 (see also Andrews 1971a) and need not be considered here. However, the form in which these data are collected and the errors involved require some discussion.

Till fabric data are most commonly collected in two forms as follows.

- (a) The orientations* of each pebble are recorded without regard to the angle of dip; thus each observation is represented by two azimuths 180° apart. This gives a circular distribution to the data and the fabric is therefore said to be two-dimensional.
- (b) Orientation is measured with reference to the dip of the particle, which by convention is down-dip from the horizontal. In this form, a sense of direction is given to the observation, which makes the data unique over a 360° range. This is a spherical distribution and is therefore termed a three-dimensional fabric**.

(ii) The accuracy of till fabric data collection.

The field procedures used in the collection of fabric data have remained largely unaltered (for exceptions, see Karlstrom 1952; McGown and Derbyshire 1974) and are subject to numerous errors, which may not always be of a random nature. These errors require consideration before reviewing the statistical techniques that have been

* In this discussion, the terms "orientation" and "dip" refer to the attitude of individual pebbles measured, while "trend" and "plunge" correspond to the attitude of the entire sample.

** The examples used in this study have all been measured in three dimensions. In the review of two-dimensional statistical tests, three-dimensional fabrics have been analysed by reducing them to a semicircular range.

used to analyse till fabric data, for the tests are only as effective as the data are considered accurate.

- 1) Errors occur in replacing the pebble in its original position after inspection to determine the a-axis; this is especially the case in coarse, gravelly till.
- 2) Errors occur in assessing the correct position of the a-axis after replacement of the pebble (Kauranne 1960; Hill 1968).
- 3) Errors occur in aligning the compass with the position of the a-axis (Hill 1968) or the clinometer with the dip of the a-axis (Krüger 1973).
- 4) Errors occur in reading or recording the values.
- 5) The subjectivity involved in the initial selection of pebbles for measurement, in terms of those rejected and those measured, vary from worker to worker and this can lead to variations in the form of the fabric that is produced (Griffiths and Rosenfeld 1954; Hill 1968; McGown and Derbyshire 1974; Drake 1977).
- 6) Results may be affected by magnetic errors, in that variable declination may be produced by local magnetic anomalies, magnetic boulders or pebbles within the till or underlying bedrock (Kauranne 1960).
- 7) Results may be influenced by rejection from the analysis of clasts that exceed a certain dip value (Andrews and Smith 1970).
- 8) Errors may be introduced if the fabric is sampled from a vertical face as opposed to one that is horizontal. Andrews (1971a) has observed that when sampling a vertical face there is a temptation to select pebbles projecting from the face.

- 9) Vertical face sampling may also produce more serious errors in that numerous workers have found that till fabrics vary considerably over short vertical distances (Kauranne 1960; Andrews and Shimizu 1966; Johansson 1968; Young 1969; Boulton 1971).

(iii) The statistical analysis of till fabric data.

The use of graphical techniques in the form of rose or contoured polar diagrams has long been employed to illustrate till fabric results. From such diagrams preferred trends can be estimated by inspection, but in many there is a need for an objective statistical method for obtaining the strength and the significance of this direction. Curray (1956) has suggested that the requirements for any statistical analysis of orientation data in both two and three dimensions should be

- 1) a measure of the central tendency or preferred trend in the data, which is independent of origin;
- 2) an estimate of the degree of dispersion about the preferred trend (ideally, independent of any *a priori* point of origin); and
- 3) a test of the significance of the results against an alternative model, usually a random or a uniform distribution.

Various procedures have been devised to help accomplish one or more of the above steps, and these have been reviewed by Krumbein (1939), Flinn (1958), Pincus (1956), Steinmetz (1962) and Andrews (1971a). Early statistical analyses of till fabric data were undertaken in

a two-dimensional framework (e.g. Krumbein 1939; Curray 1956; Harrison 1957b; Kauranne 1960; Andrews 1963b) but, with increasing interest in the analysis of the dip of pebbles in till, techniques for deriving three-dimensional solutions have been developed (e.g. Andrews and Shimizu 1966; Ramsden 1970; Mark 1971, 1973).

Although numerous methods now exist for the analysis of till fabric data, comparisons of the different methods have rarely been made. Moreover, many workers have failed to consider fully the assumptions that underlie the statistical tests they have used and consequently, in some cases, spurious results have been obtained.

Two characteristics of till fabric data tend to complicate analysis. First, the data in many fabrics are bimodally or multimodally distributed. The existence of more than one mode violates the assumptions of a normal distribution, yet the latter is often the basis on which statistical analysis of till fabrics is carried out. Secondly, the circular or spherical (if a three-dimensional solution is required) distribution of the data means that there is no logical point of origin, except that established by convention. Moreover, the point of origin (usually north) from which orientation values are measured is arbitrary; this may cause inconsistencies in the use of certain techniques, as discussed below.

The following section of this chapter is divided into three parts:

- 1) a critique of the two-dimensional statistical analysis of till fabric data;
- 2) a critique of the three-dimensional statistical analysis of till fabric data;

- 3) a general discussion and conclusions outlining a methodology for the statistical analysis of till fabric data.

The first two parts consider the statistical assumptions of each technique used, their application to till fabric analysis by various workers and a discussion of their advantages and disadvantages. The third part presents the methodology used by the present writer in analysing the till fabric data given in the second half of the chapter.

11.2.2 The two-dimensional analysis of till fabric data.

Introduction

Most of the analysis of till fabrics in two dimensions has been carried out by using one of four procedures; other methods, including that developed by Thomas (1967), have been employed on only a limited scale. These four procedures are:

- 1) the linear transformation method;
- 2) two-dimensional vector analysis, including the Rayleigh test;
- 3) the chi-square test;
- 4) the Tukey chi-square test.

Each of these methods of analysis is described and discussed below.

The linear transformation method

Krumbein (1939) was the first worker to outline a method for the statistical analysis of till fabric data in two dimensions. He suggested that the original circular data should be converted into a linear form with a semicircular (180°) distribution; this transformation is carried out by combining diametrically opposite azimuthal classes. Using this procedure, any diametrically opposite modal

peaks would be cancelled out (see Figure 11.1). In Figure 11.1(a) two modes are present in the data, at 100° and 280° . When the histogram is resolved into a semicircular distribution, these two modes are combined to produce a peak at 100° (Figure 11.1(b)). The modal peak is then rotated, by choosing an arbitrary point of origin, such that it is positioned symmetrically about the centre of the abscissa on the histogram.

After centring the distribution, Krumbein applied conventional linear methods of moment calculations to the data in order to determine the mean trend of the fabric and the dispersion of observations about the mean by calculating the standard deviation. The application of the linear transformation method to till fabric data has been carried out on only a limited scale (Hill 1968; Saunders 1968).

There are two major disadvantages to this method. First, the analysis is dependent upon the choice of the point or origin whereby the circular distribution can be divided into a linear frequency histogram. Jizba (1953) and Chayes (1954) argued that a change in the choice of only one class interval, or by even a few degrees, can make considerable differences in values obtained for the mean and standard deviation. Secondly, the mean and standard deviation results will be affected if, after transformation and rotation of the data, more than one mode is still present within the semi-circular range. For example, the till fabric presented in Figure 11.2(a) shows two modes occurring at 340° and 20° , while the mean trend, at 10° , occupies an intermediate position between them (Figure 11.2(b)). Moreover, spurious results will also be obtained if the same procedures are applied to fabric data that are strongly skewed or possess

Figure 11.1 **Linear transformation procedure of Krumbein (1939)**
using data with diametrically opposite modes:
a. 360° frequency histogram;
b. 180° frequency histogram.

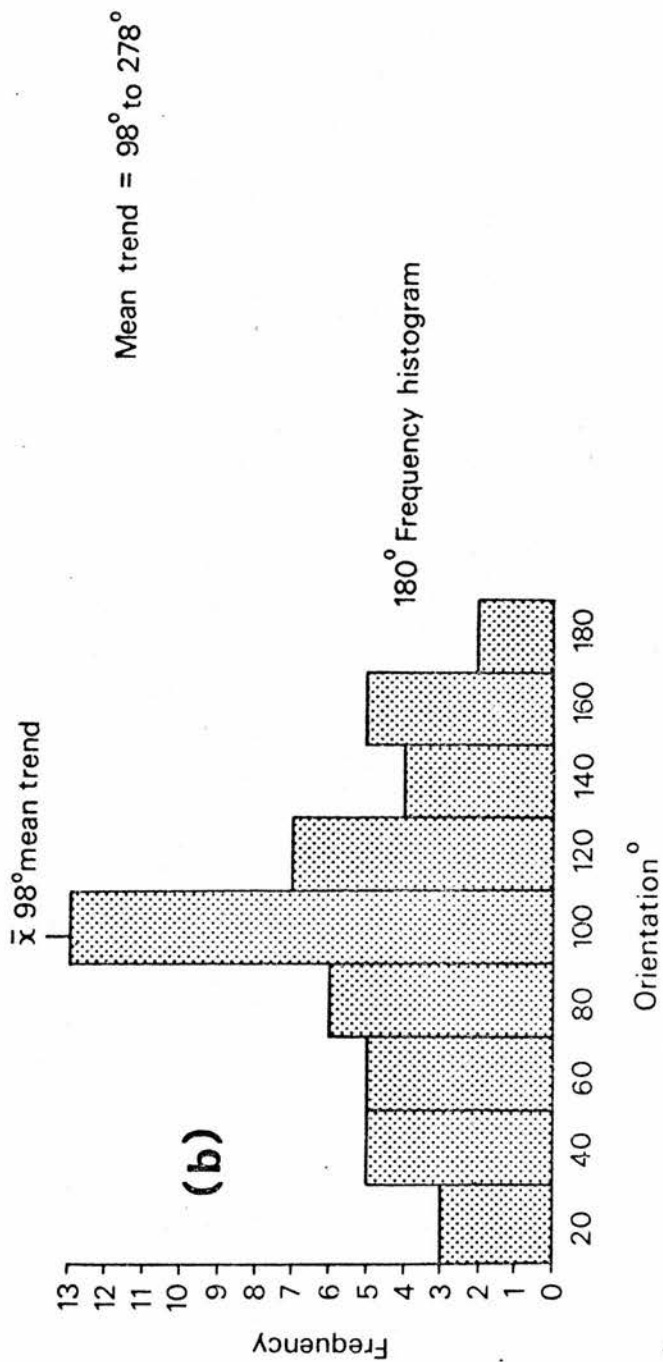
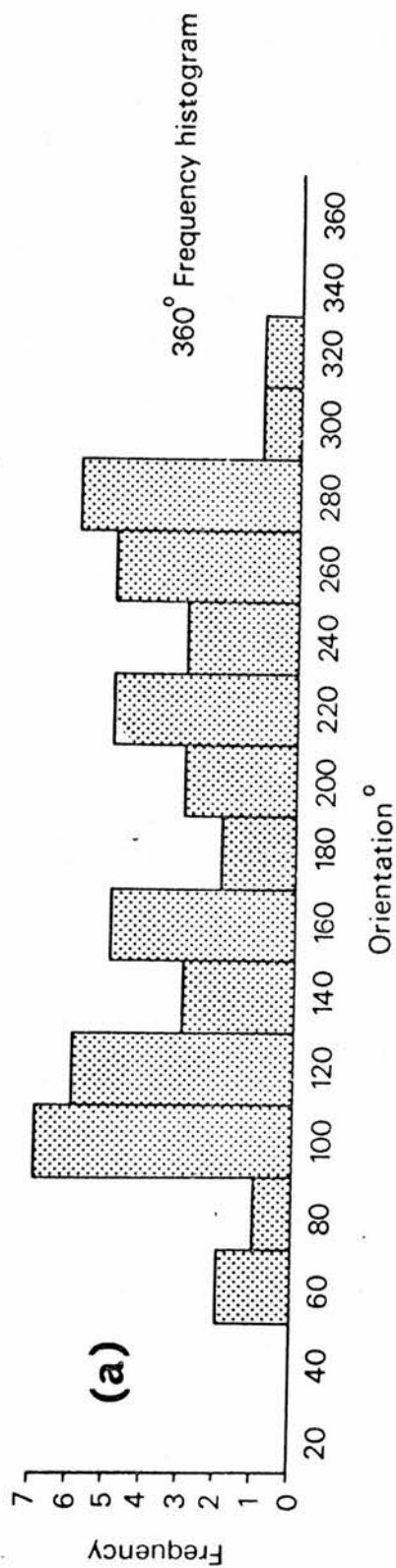
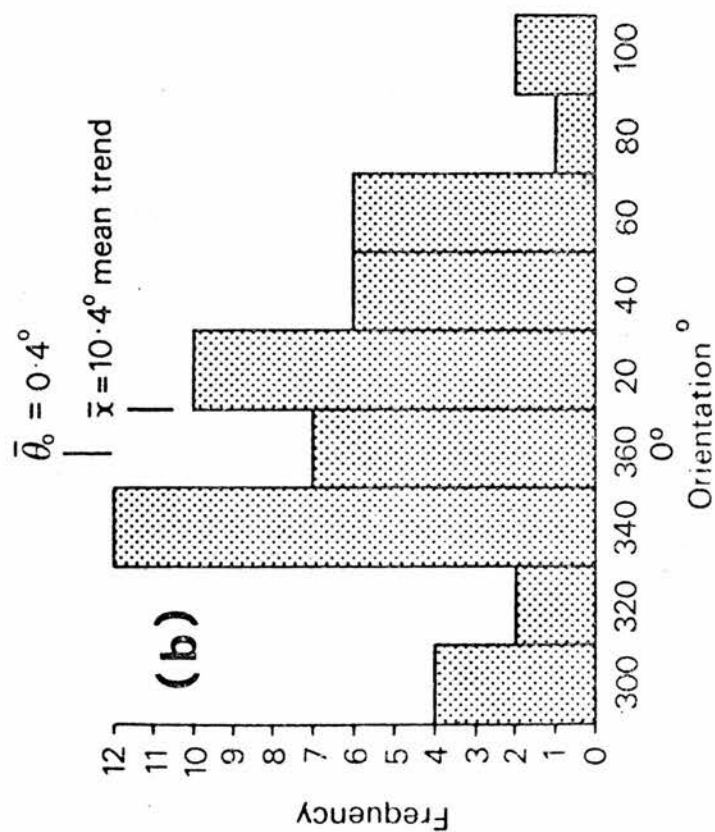
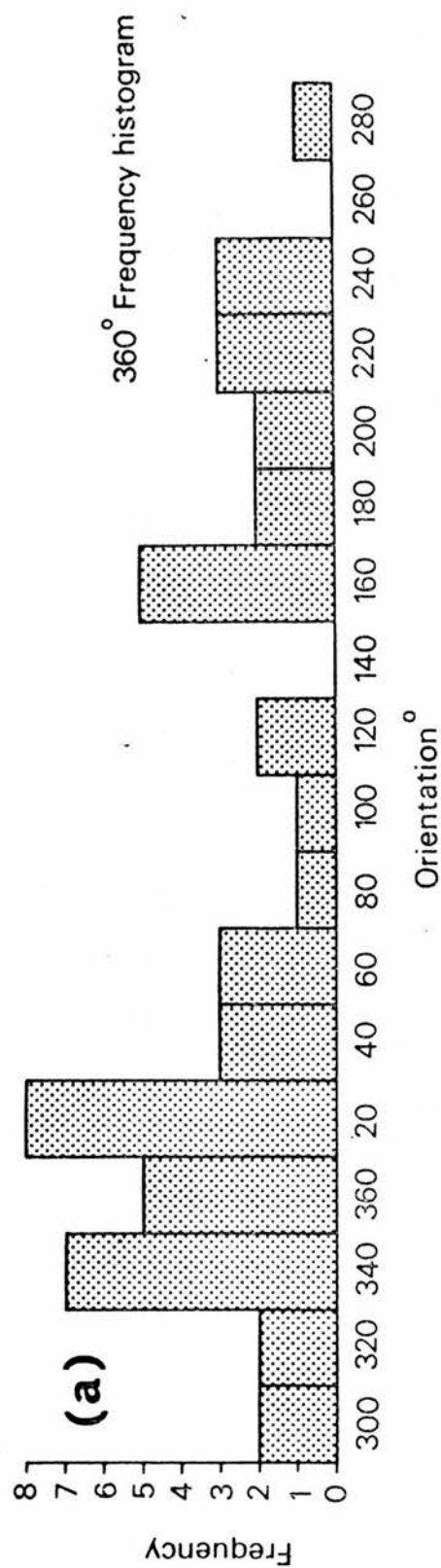


Figure 11.2 **Effect of a bimodal distribution on the linear transformation procedure of Krumbein (1939):**

- a. 360° frequency histogram;
- b. 180° frequency histogram, mode positioned at the centre of the abscissa of histogram.



a large dispersion.

Two-dimensional vector analysis

An alternative method for analysing orientation data, involving two-dimensional vector summation techniques, was introduced by Reiche (1938) and subsequently applied to the analysis of pebble orientations in till by Krumbein (1939).

As the measurement of the orientation of pebbles in two dimensions makes no distinction between one end of the pebble and the other, each measurement is unique only over a 180° range. Thus Krumbein grouped the observations into class intervals extending over this range. However, in a semicircular distribution north and south components will tend to cancel each other, but there are no west components to cancel the east components, which can lead to the calculated vector giving spurious results.

To overcome this problem, Krumbein doubled the angles of the class midpoints before computing each radius vector, thereby converting the distribution to a nonsymmetrical form. Each radius vector is then resolved into perpendicular horizontal (east-west) and vertical (north-south) components and the resultant vector or vector mean direction ($\bar{\theta}_0$) is computed using the expression:

$$\bar{\theta}_0 = \frac{1}{2} \arctan \left(\frac{\sum N \sin 2\theta}{\sum N \cos 2\theta} \right) \quad (1)$$

where θ is the midpoint of each class (between 0° and 180°) into which observations are grouped, and N the number of observations in that class. Using this procedure, vector analysis yields two possible solutions for the trend of any fabric, namely $\bar{\theta}_0$ and $(\bar{\theta}_0 + 180^\circ)$, and these should be stated on the fabric diagram.

In 1956, Curaray published a paper extending the vector summation technique by computing the vector magnitude as a measure of dispersion. This value is calculated using the expression:

$$r = \sqrt{(\sum N \sin 2\theta)^2 + (\sum N \cos 2\theta)^2} \quad (2)$$

where r is the magnitude of the resultant vector (i.e. an estimate of the variance about the resultant vector). Further, Curaray provided a procedure to test the significance of the vector magnitude; this he termed the Rayleigh test (after Rayleigh 1894, see also Norcliffe 1977). The test is applied by converting the vector magnitude into a percentage figure using the expression:

$$L\% = \frac{r}{\sum N} 100 \quad (3)$$

where L is the vector magnitude in terms of per cent* and N the number of observations. The value of L is then compared with a graph to determine whether the sample distribution departs significantly from one that is random at a given level of significance.

The provision of a test of significance, and the fact that the results are calculated independently of any *a priori* reference direction of origin makes the technique more objective than the linear rotation method. Consequently, the two-dimensional vector summation in combination with the Rayleigh test has been used quite extensively in the analysis of till fabrics (for example, Young 1969; Krüger 1970; Hill 1971; Rose 1974).

There are, however, certain drawbacks to the method. The

* The $L\%$ value is independent of sample size and hence can be usefully employed in comparing different samples.

assumption that the sample distribution is drawn from a circular-normal distribution is fundamental to vector analysis, as the test is designed to recognise the presence of a single, preferred trend in the data. This, however, is not always the case with till fabric data, for most exhibit bimodal or multimodal characteristics. Thus, as the data are reduced to a semicircular range before analysis, the presence of two modes within this range will lead to a preferred trend being identified that occupies an intermediate position between each mode. This drawback has already been mentioned with reference to the linear rotation technique. In the example quoted above (Figure 11.2), the r value for the fabric has also been included, and can be seen to lie at 0.4° .

The chi-square test

The arguments and examples presented above indicate that sample fabric data do not always approximate the circular-normal distribution required for vector analysis. To overcome this problem, the chi-square test (on a null hypothesis of a uniform distribution) has been used as a measure of isotropicity in till fabrics by numerous workers (e.g. Harrison 1957b; Kauranne 1960; Kirby 1961; Andrews 1963b; Smithson 1965; Andrews and Smithson 1966; Cowan 1968; Harris 1969; Hill 1971; Mark 1971; Reheis 1975; Mills 1977b).

The form of the chi-square equation as used in such studies is one in which the expected values are known and uniform:

$$\chi^2 = \frac{1}{E} \sum_{j=1}^k (O_j - E)^2 \quad (4)$$

where O is the observed frequency for each cell, E is the expected

frequency for each cell and k is the number of cells. If a sample comprises n measurements then $E = n/k$. Each cell consists of equal sectors of a circle, and the observations are grouped within the appropriate sectors. By convention, the expected frequency (E) for each cell should exceed 5.0 (Chayes 1949; Dixon and Massey 1969). Thus for sample size n , the number of sectors employed should not exceed $n/5$. For this reason, the observed frequencies in diametrically opposite sectors are often summed. This allows the technique to be used on smaller samples without the loss of precision that would result from reducing the number of sectors and hence increasing their size.

The sample size necessary to identify preferred trends in till fabrics has received much discussion in the literature. Harrison (1957a) suggested that a sample size of 25 pebbles is sufficient, whereas Krumbein and Pettijohn (1938) maintained that at least 100 pebbles should be measured. However, sample sizes of either 50 (e.g. Järnefors 1952; Hoppe 1952; West and Donner 1956; Wright 1957; Norris 1962; Michelson 1973) or 100 (e.g. Holmes 1941; Beaumont 1971a; Penny and Catt 1967; Niewiarowski 1969; Drake 1971) orientation measurements have been most frequently employed, and where the chi-square test has been employed it has been usually based on a sector size of 20° . Where the sample size is 50, use of a 20° interval necessitates summation of diametrically opposite sectors to give $k = 9$ and hence, $E = 5.555$. With a sample size of 100, the above procedure is unnecessary for $k = 18$ and E is again 5.555.

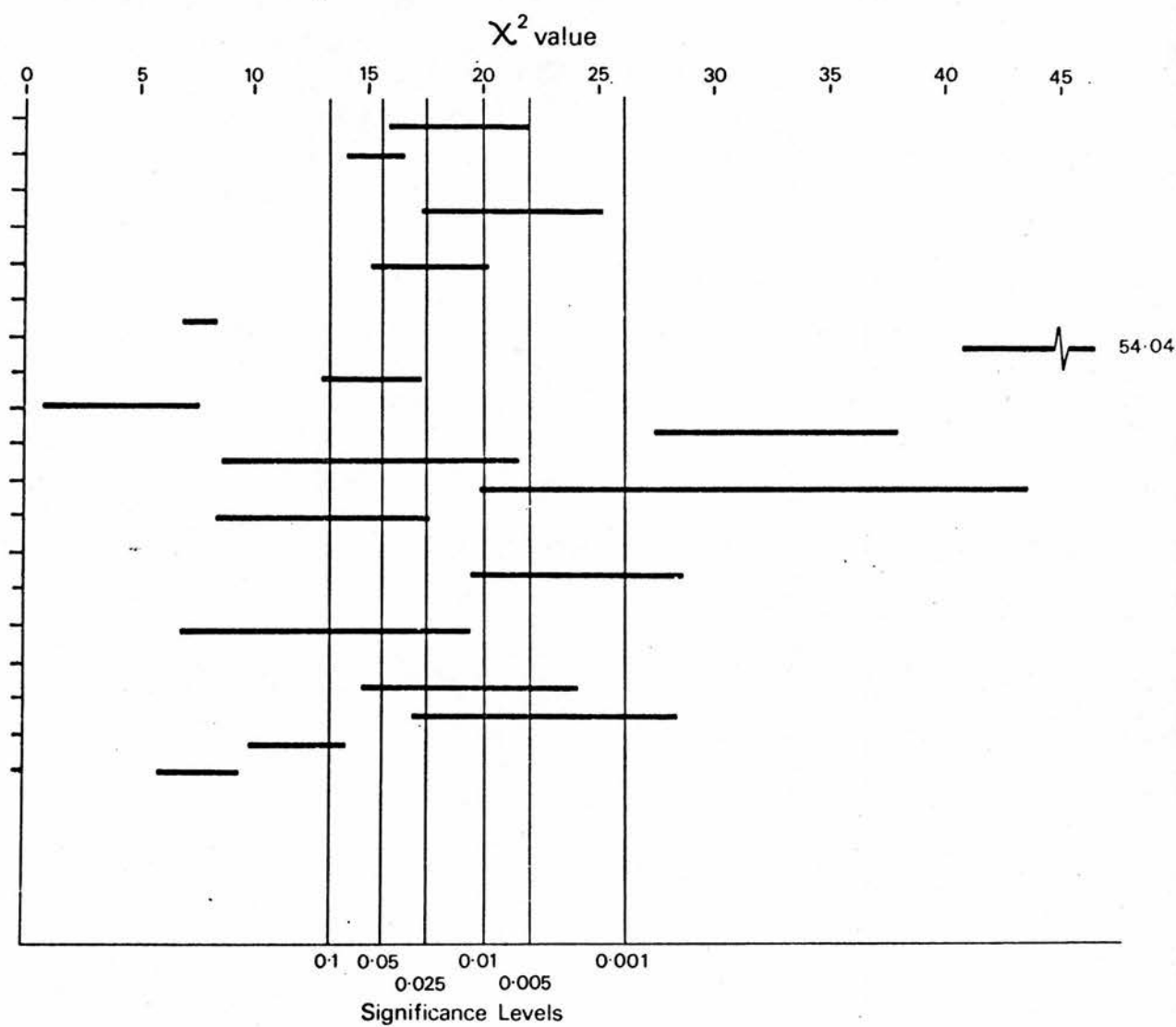
The chi-square statistic has several advantages over the linear rotation and two-dimensional vector summation techniques, in that it is easily computed, and being non-parametric is appropriate for the

analysis of non-normal circular distributions with a single, dominant mode. Moreover, the uncomplicated nature of the test reduces the possibility of overinterpretation of the results, a danger latent in more sophisticated techniques (see below).

Although the chi-square statistic is versatile and provides a test where the statistical assumptions relating to the form of the data are not too rigorous, there are certain drawbacks to the technique. These are as follows.

- 1) Chi-square yields no indication of the distribution (areal) of points on any fabric diagram, in that the same χ^2 value may be obtained from more than one distribution of n points (Pincus 1953).
- 2) The chi-square test uses a two-dimensional frame of reference, but till fabric data are usually collected in three dimensions (i.e. orientation and dip). As such, the statistic cannot be used to determine the direction of any plane of orientation within the data.
- 3) As the data are grouped into sectors that have a circular range, then the χ^2 values will be sensitive to the point of origin from which the pattern of sectors is generated. Arbitrary selection of the point of origin can lead to differences in the size of the observed frequency within each sector (Jizba 1953; Pincus 1953; Chayes 1954; Jones 1968). Consequently, the calculated χ^2 value will also vary and thus any single χ^2 result must be treated with caution (Ballantyne and Cornish 1979). To assess the extent of this variation, all possible χ^2 values were computed for 18 sets of till fabric

Figure 11.3 Range of calculated chi-square values for
18 sets of till fabric data.

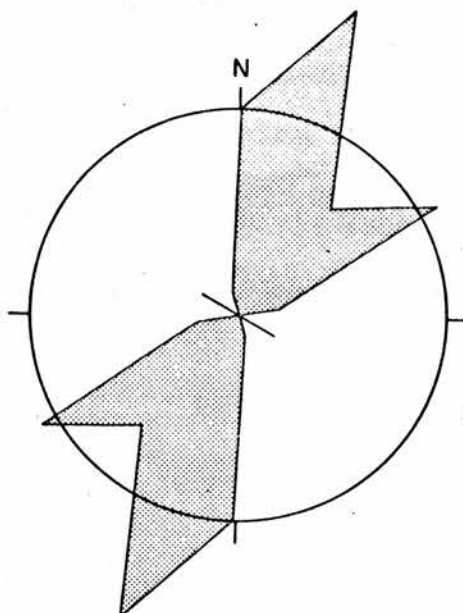


data drawn at random from a total of 36 fabric samples measured from the cross-valley ridges located in the Carsphairn area. In these fabrics the orientation of 50 pebbles was measured to the nearest 5° , and in order to satisfy the convention of $E \geq 5.0$, the data were grouped into nine sectors of 20° , using summation of frequencies in diametrically opposite sectors as described above. The results of this analysis are presented in Figure 11.3, from which it is apparent that the range of calculated χ^2 values is unacceptably large. For 5 of the 18 samples, the maximum χ^2 value is twice as large as the minimum value. Moreover, the range of χ^2 values calculated for 11 of the 18 samples transgresses more than one, and in three cases four, of the six commonly-used levels of significance shown in Figure 11.3. Clearly, this indicates that the level of significance obtained is entirely dependent on the point of origin chosen when the chi-square calculation is performed. This suggests that the test as employed in the form outlined above may give arbitrary results.

- 4) Although the chi-square test is able to identify whether any distribution differs significantly from one that is uniform, it can give ambiguous results for distributions that are strongly bi- or multimodal. For example, Figure 11.4(a) and (b) show unimodal fabrics with minor secondary modes of varying magnitude. It is clear in these examples that the null hypothesis of uniformity would be rejected, as the combining of diametrically opposite frequencies will produce a single, dominant mode. Figure 11.4(c) shows a fabric with

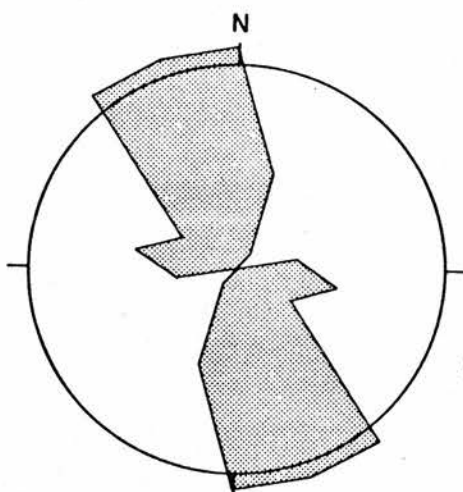
Figure 11.4 Two-dimensional till fabric diagrams showing
results of chi-square analysis.

a



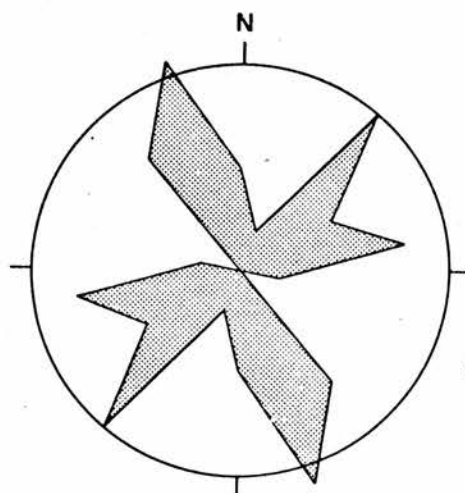
Standard χ^2 test = 50.59*

b



Standard χ^2 test = 26.59*

c



Standard χ^2 test = 20.77*

Circle represents 20% of observations

* significant at 0.01 level

n = 50 pebbles

Class Interval = 20°

two modes that lie at right angles to each other. Again, the null hypothesis is rejected, but the results are ambiguous, for both modes, after summing, lie in the same semicircular range and have approximately the same magnitude.

- 5) The chi-square test does not provide a measure of the central tendency of any fabric (Kauranne 1960; Andrews 1963b; Andrews and Smithson 1966).

The Tukey chi-square test

Following from the suggestions outlined by Krumbein (1939) and Tukey (1954), a combination of the chi-square and two-dimensional vector summation techniques was applied by Harrison (1957b) to the analysis of pebble orientations in till. This method yields a value for the mean trend of the fabric, plus a measure of its statistical significance as compared with a uniform distribution. Although superior to the conventional chi-square test of Kauranne (1960), the technique suffers from the same drawbacks outlined above with reference to the chi-square test and the vector summation technique.

11.2.3 The three-dimensional analysis of till fabric data.

Introduction

The measurement of a pebble a-axis in three dimensions is usually recorded as orientation and dip, with the latter being measured downward from the horizontal plane (Holmes 1941). There is no conceptual basis for this procedure, which is conventionally employed to enable an unambiguous presentation of three-dimensional orientations.

Statistical analysis of till fabric data in three dimensions

was first attempted by Andrews and Shimizu (1966). This and subsequent work by Andrews based largely on vectorial methods, which have been designed for analysis of palaeomagnetic data, has led to the establishment of a series of procedures, which although rigorous in their original application can, however, be shown to be less so when applied to certain till fabric data. In addition, a procedure that involves the calculation of eigenvectors has recently become favoured by workers analysing till fabrics in three dimensions (Mark 1973). Although this method does not possess the same statistical assumptions as the three-dimensional vectorial approach, certain assumptions have been overlooked by some workers employing the technique. Therefore this section will consider aspects of the application of these two techniques to the analysis of till fabric data.

Before reviewing the applications it is necessary to define the terms used and also to summarise the statistical procedures in the context for which they were originally designed.

The attitude of any object in three-dimensional space can be defined by a conventional system of three mutually perpendicular axes. This may have an orientation that is "directed" (i.e. it has a north and a south pole) or "non-directed" (i.e. the poles are undefined) (Scheidegger 1964). The orientation of the a-axis of a pebble in a till is an example of a non-directed orientation, unless it can be related with certainty to the direction of former ice movement. On the other hand, the orientations of palaeomagnetic observations are directed, because the poles are specifically defined.

A Vector is a quantity that has three properties:

(a) orientation, (b) magnitude and (c) sense (Steinmetz 1962). If a phenomenon does not possess all the above, then it is not a vector.

When vectors are used to represent the attitude of pebbles in till deposits:

- (i) vector orientation is determined by the direction (trend) of plunge and the angle of plunge;
- (ii) vector magnitude is defined by an arbitrary value given with equal weight to all observations; and
- (iii) vector sense is determined on the geomorphological assumption that the mean plunge of the pebbles is up-glacier. Clearly, this assumption can only be applied if the direction of former ice movement is known. If it is not, then the data will not possess vector sense and as such the pebble orientations will be non-directed.

Scheidegger (1964, p.1521) focused attention on this latter aspect, stating that with the construction of "a vector-sum of such (non-directed) axes, it would not be clear in which direction the axes should be assumed to 'point'".

It is clear therefore that in terms of the above arguments, the application of vectorial procedures to the analysis of till fabrics requires very careful formulation.

The vector summation technique

Fisher (1953) developed a theory of a spherical-normal probability distribution designed to estimate the mean of a set of directed orientations (in this case geomagnetic vectors) grouped around a single direction on a sphere. This pioneer work was extended by Watson (1956a,b) and Watson and Irving (1957). In this

last publication the Fisher distribution was employed in the development of a three-dimensional procedure for the statistical analysis of palaeomagnetic vectors. Basically, this is as follows:

- (i) the calculation of the best estimate of the mean polar direction;
- (ii) the calculation of a precision parameter ("K"), which is a measure of the concentration of the grouping in the mean polar direction;
- (iii) the application of Watson's (1956b) test of randomness to the data, which is designed to compare a set of individual vectors whose sample space corresponds to a sphere; and
- (iv) the calculation of ω and β precision parameters, which provide an indication of within- and between-site variability.

However, this method of treating vectors is designed to be applied when the basic form of the distribution is known to approximate a spherical-normal distribution (Jeffreys 1948). Moreover, Green (1964) urged that caution should be exercised when using the technique, for if employed on bi- or multimodal data spurious results are liable to be produced. In reply to the latter criticism, Steinmetz (1964) suggested that it is not any more invalid to apply the technique to multimodal data " . . . than it is to assume a Gaussian distribution and apply 'normal' statistics to bimodal grain size analyses" (p.442). This is a fallacious argument and fails to meet Green's comments. The assumptions underlying any statistical test must be adhered to and the correct technique applied to the specific form that the data take, otherwise the results may be spurious. This point has also been

argued with reference to the analysis of particle-size parameters (Chapter 8).

The vector summation technique of Fisher was specifically designed for use on unimodal, directed orientations. Thus, any orientations to which the method is applied must be in the form of vectors. However, as shown above, where direction of former ice movement is unknown, pebbles measured in till deposits do not possess vectorial properties. Therefore in order to fulfil these requirements it is necessary to assign vector sense to the pebble orientation (Steinmetz 1962; Scheidegger 1965). This is carried out by cutting the distribution in half (using a plane of reference), so that instead of considering a spherical distribution only that part of the distribution lying in a given hemisphere is considered. The resulting vectors are then treated as having a Fisher distribution. The best approximation to this is obtained when a sense is assigned to the orientations using a reference plane that lies at right angles to the central tendency of the grouping (Pincus 1953).

While the hemisphere adequately defines the original spherical distribution (it being simply the diametrically opposite image of the other hemisphere), it should not be considered as being the same, since the original spherical distribution comprises two hemispheres. Using this procedure, when the non-directed orientations have a unimodal distribution, it is possible to calculate a best estimate of the mean trend if care is taken in the selection of the right hemisphere to be used.

The application of the vector summation technique to till fabric analysis. Andrews and Shimizu (1966) experimentally adapted the

vector summation method for the calculation of certain till fabric parameters. They argued that the conventional horizontal plane of reference, used in recording the dips of pebbles, was not necessarily the most appropriate for the statistical analysis of till fabrics, suggesting that a subglacial slope may have existed during deposition of the till and the plane of deposition may have been sloping and that under these conditions reference to a horizontal plane could be misleading. To overcome this apparent problem Andrews and Shimizu suggested that some form of rotation of the data, in order to "cluster" the points, might produce a significant trend. They defined an eight point procedure for the analysis, which was implemented by a FORTRAN IV computer program. Here individual vectors were assigned to the downdip ends of the a-axes of the till pebbles as specified by their orientation and dip; thus all the resulting vectors occupied the lower hemisphere. The direction and magnitude ("R") of the resultant vectors were calculated, plus and estimate "K" of Fisher's precision parameter (using a formula provided by Watson (1956a)). Andrews and Shimizu found that the maximum values for the "R" and "K" parameters were obtained from a 90° rotation of the data, and concluded that this was the best rotation for use in the three-dimensional analysis of till fabrics.

This method was also employed by Andrews and King (1968): the "R" and "K" tests were again applied and a 90° rotation of the data used, with the axis of rotation passing through the area with minimum observations. In addition, estimates of the ω and β parameters were calculated in order to examine within- and between-site variability of fabrics.

In 1970, Andrews and Smith published details of an investigation into till fabric methodology, the culmination of work that had been preliminarily reported four years earlier (Andrews and Smith 1966). Fifty till fabrics from the cliffs along the north Yorkshire coast were analysed using the three-dimensional techniques outlined by Andrews and Shimizu (1966). This time, however, only 40° rotations of the data were employed for, as they claimed, "this figure represented the average minimum variance solution" (1970, p.523).

Ramsden (1970) modified the Andrews and Shimizu procedure by assigning vectors to pebble axes such that they lay in any hemisphere, the desired hemisphere being specified by the orientation and dip of its axis. A second modification by Ramsden involved a method of locating the optimum position of the hemisphere, thus producing (in theory) a set of vectors most closely approximating a spherical-normal distribution. Ramsden termed this the "mean vector program" (1970, p.54).

Mark (1971) followed Ramsden by publishing a FORTRAN program to implement a series of rotations of the data in order to provide the "best-fit" for the maximum mean vector length; from this the trend and plunge of the mean vector were determined. A chi-square statistic was also incorporated into the program to test whether the data were "non-random" (Mark 1971, p.2663) at a given level of significance. Otherwise, the parameters calculated by the program are the same as those provided by Andrews and Shimizu (1966). Using this procedure, Mark (1971) analysed 42 fabrics three times using 5° , 10° and 20° intervals between each rotation. He suggested that the 20° interval was acceptable as the accuracy of the till fabric

data collecting process was low. Further, he found that a 90° rotation of the data provided the maximum vector length in 78 per cent of the samples analysed. However, where this rotation (i.e. 90°) was "forced" (1971, p.2663) on the remaining 22 per cent of the samples, the trend of the mean vector changed by up to 14° .

Apart from Andrews and his co-workers, few researchers have attempted to apply three-dimensional vector summation procedures to the analysis of till fabric data. Cowan (1968) employed the Andrews and Shimizu procedure in combination with a chi-square test on a plot of the a-axis orientations of till pebbles in order to determine the trend of fabric maxima. In his paper, only tables of the values and their levels of significance were presented; fabric diagrams were not included. Finally, Boulton (1970b, 1971) utilised the vector summation technique (following Steinmetz 1962) in the study of tills derived from glaciers on Spitzbergen, as did Shaw (1971) in his analysis of till deposits from the Shrewsbury area, England, and Baker (1976) analysing soliflucted till deposits in the Cam valley, north Essex.

Discussion of the application of the vector summation technique to till fabric analysis. The major assumption underlying the rationale used by Andrews and Shimizu for applying the vector summation technique to till fabrics is that " . . . pebbles will cluster about a mean direction and will have a tendency to plunge up-glacier" (1966, p.158). From this statement, they proceeded to assume that the resulting ideal distribution would be spherical-normal.

However, the traditional view regarding up-glacier imbrication of pebbles in till is open to question. These doubts are based on the following considerations.

- 1) The still incomplete knowledge of what processes impart the fabric to a till deposit. Here, it is important to consider the type of till being analysed; the premise that till fabric analysis can be employed to infer mode of lodgement and direction of ice movement (see for example: Harrison 1957a; Wright 1957; Andrews and Smith 1970) does not always hold, in that the distinction between ablation till (including flow tills), melt-out tills and lodgement tills *sensu stricto* cannot be made merely on visual inspection (Boulton 1971, 1972a; Rose 1974).
- 2) The possible glacial modification of till fabrics. Here, two aspects are of importance. First, the original fabric of englacial debris (i.e. with a high up-glacier imbrication, if a single shear domain is operating (Lindsay 1970)) is likely to be destroyed upon melt-out of the till. Boulton (1970b, 1971) has suggested that a fabric pattern parallel to the surface of accumulation may be produced. Secondly, fabrics may become re-orientated by the action of over-riding ice masses (MacClintock and Dreimanis 1964; Ramsden and Westgate 1971).
- 3) Complications that may affect the depositional process of lodgement till. These include:
 - (i) the form of the bedrock surface, which influences till deposition and therefore its fabric (Boulton 1970b, 1971; Nobles and Weertman 1971);
 - (ii) the relative movement of pebble clasts around large boulders within the till (Miller 1884; Virkkala 1960);
 - (iii) the effect of folding and other glacitectonic structures

on till fabric (Banham and Ranson 1965; Banham 1966, 1975; Penny and Catt 1967);

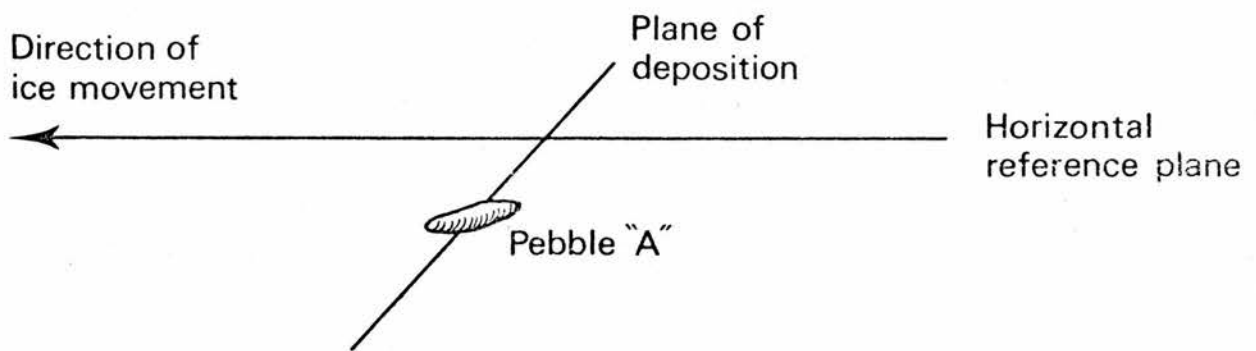
- (iv) the possible post-depositional modification of the fabric by solifluction, slumping, frost heave or soil creep;
- (v) the influence of clast shape on the nature of the till fabric (Holmes 1941; Andrews and King 1968; Krüger 1970; Ramsden 1970; Drake 1974, 1977);
- (vi) the angle of the plane of deposition of the till (Lindsay 1970). For example, in the idealised case shown in Figure 11.5, pebble "A" dips down-glacier if measured with reference to the horizontal, but it was actually deposited with an up-glacier dip.

Thus there are reservations about the use of the up-glacier imbrication of pebbles in till for defining the direction of ice movement. It follows, therefore, that the generalisation made by Andrews and Shimizu regarding the plunge of pebbles in till is questionable. Consequently, the assignment of a sense to the a-axis of any till pebble on the above assumption is not necessarily valid. This latter point also implies that the direction of ice movement is known, yet this is what the till fabric analysis, in this case, is being employed to determine.

A second major flaw that vitiates the vector summation procedure as used by Andrews and Shimizu (as well as by Mark 1971) is that pebble orientations are assumed to be unimodally distributed within a selected hemisphere: in other words, that the data approximate

Figure 11.5 The dip of a pebble in relation to its plane
of deposition in till.

The dip of a pebble in relation to its plane of deposition in till



a spherical-normal distribution. However, if the actual distribution is bi- or multimodal then the results produced may be meaningless, for the tests have been specifically designed for use on unimodal data. These grounds were used by Ramsden (1970) to criticise the procedure (as well as his own modification of it) and the associated significance tests. In doing so he outlined three main flaws.

- 1) The use of the test for randomness (Watson 1956b) was wrongly applied in that it was designed for the analysis of vectors with a spherical-normal distribution on a sphere. However, as shown above, in order to treat pebble axes as vectors this distribution must be cut in half and made to lie in a selected hemisphere. Yet this distribution represents a clustering when compared to a random distribution over a whole sphere. Thus the "R" values will always give high significance values (i.e. indicating a non-random distribution) even though the distribution within a hemisphere may be random.
- 2) The precision parameter "K" is used incorrectly. The parameter is employed in an attempt to distinguish spherical-normal distributions from other kinds of distribution. This approach is invalid, for the parameter gives information about the shape of the spherical-normal distribution only when the distribution is known to approximate spherical-normal.
- 3) The calculation and employment of the $\hat{\omega}$ and $\hat{\beta}$ statistics are invalid when applied to distributions that are not spherical-normal about their means.

In this context, it should also be noted that the actual selection of the reference hemisphere, mentioned above, is open to

criticism. Andrews and Shimizu (1966) assumed that the a-axis of a pebble is downward pointing, the horizontal being regarded as a plane of reference from which a sense is assigned to the pebble axis. Mark (1971) assumed the sense to be arbitrarily determined as lying below a plane of reference, which need not necessarily be horizontal. However, whatever method is employed, the final result will not be independent of the choice of plane (which it should be (Scheidegger 1964)).

Moreover, Pincus (1953) indicated that the most effective means of dealing with data that display a spherical-normal distribution and lie in a hemisphere occurs " . . . where the plane of cut along the open side of the hemisphere is a maximum (perpendicular) distance from the centre of gravity of the points plotted on the hemisphere" (p.506). Thus it is not surprising that in the majority of fabric analyses carried out by Andrews and Shimizu (1966), Andrews and King (1968) and Mark (1971), the data had to be rotated through 90° in order to maximise the above-mentioned distance and in doing so effectively make the vectors assume a spherical-normal distribution.

Finally, the problem of unimodality of till fabric data is intrinsically linked to the presence of transverse modes in fabrics. This aspect was mentioned by Andrews and Shimizu, who suggested that they " . . . do not contribute any significant information to the analysis and may, therefore, be considered anomalous" (1966, p.160). In order to overcome these difficulties, they suggested that 10 per cent of the observations lying $\pm 90^{\circ}$ from the preferred trend after a 90° rotation should be "omitted from the calculations and the results rerun" (1966, p.160). Having carried out this operation on

their fabrics, the statistical significance of each showed a marked increase. Such a procedure is clearly highly subjective and scientifically unacceptable. The presence of transverse modes in till fabrics has been reported or discussed by numerous workers. Clearly, they are an inherent feature of the fabric (even considering the fact that pebble shape exercises some influence on the fabric, e.g. Holmes 1941; Andrews and King 1968; Drake 1974, 1977) and should be treated as such. Any attempt at removal of raw data from the analysis in order to provide higher levels of statistical significance is invalid.

In summary, it is essential that the form of the distribution of the fabric sample must be known or determined before vector summation procedures are employed in its analysis. Moreover, even when the distributions are unimodal, it must be remembered that the vector summation method of analysis is only valid if

- (i) the direction of former ice movement has been unequivocally demonstrated (i.e. by using evidence from glacial erratics, striae or ice-moulded landforms) and
- (ii) the majority of pebbles in the fabric are imbricated up-glacier.

The Eigenvalue technique

This procedure has been discussed in general terms by numerous workers including Fara and Scheidegger (1963), Scheidegger (1964, 1965), Watson (1965, 1966), Ramsden (1970), Anderson and Stephens (1971), and Woodcock (1977).

Scheidegger used a modified Gaussian distribution by introducing a $\cos^2\theta$ factor as opposed to a $\cos\theta$ factor, the latter being

used in a Gaussian (or Fisher) distribution. This means that whereas the Fisher distribution has as its sample space the sphere, the $\cos^2\theta$ distribution is restricted to the hemisphere (Scheidegger 1965). Thus any unimodal orientation may be represented in a given hemisphere without a sense having to be applied to it (Figure 11.6).

The eigenvalue method gives an estimate of the mean value of the sample and an estimate of the scattering of the points in the sample around the mean (the "standard scattering angle" (Scheidegger 1965, p.C.167)).

The potential application of the eigenvalue technique to till fabric analysis was alluded to both by Ramsden (1970) and Andrews (1971a). Mark (1973) provided the application in the form of a FORTRAN IV computer program that calculated three eigenvalues (λ_1 ; λ_2 ; λ_3) and the corresponding eigenvectors (V_1 ; V_2 ; V_3). The eigenvectors are in component form, of which:

V_1 = the maximum eigenvector, which is resolved into the primary mode (trend and plunge) of the fabric;

V_2 = the intermediate eigenvector;

V_3 = the minimum eigenvector, which is resolved into the least probable position for the pebble to take up (i.e. normal to the preferred plane of the fabric).

The eigenvalues λ_1 ; λ_2 ; λ_3 possess the property:

$$\lambda_1 + \lambda_2 + \lambda_3 = N$$

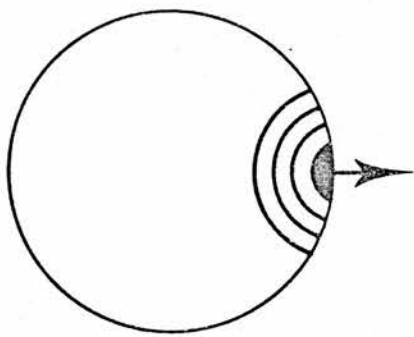
However, they are more useful in a normalised form: S_1 ; S_2 ; S_3 , and are computed by dividing the number of observations (N) in each fabric into each eigenvalue. These values possess the property:

$$S_1 + S_2 + S_3 = 1$$

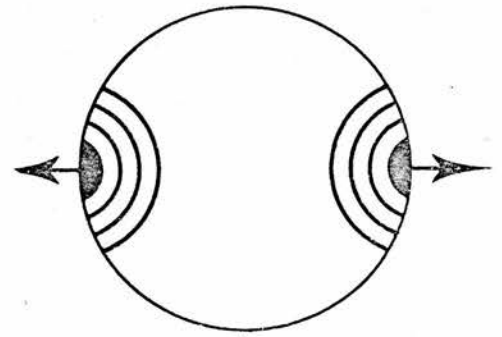
Figure 11.6

Idealised, contoured fabric diagrams:

- a. directed (vector) spherical normal distribution with sense defined;
- b. non-directed (eigenvalue) axially symmetrical distribution with sense undefined.



a



b

Idealised, contoured fabric diagrams.

- a) Directed (vector) spherical-normal distribution with sense defined
- b) Non-directed (eigenvalue) axially symmetrical distribution with sense undefined

and are a measure of the degree of clustering of data about their respective eigenvectors. The quantities S_1 (direction) and S_3 (plane) are tested against tables of significance provided by Anderson and Stephens (1971) in order to determine whether they are significantly different from values expected for a random sample drawn from a uniform distribution.

The application of the eigenvalue technique to till fabric analysis.

Mark (1974) used the technique on 28 till fabrics measured from the Sumas till in British Columbia, which had been analysed previously using the inappropriate rotational vector summation approach (Roberts and Mark 1970, 1971). Mark and Andrews (1975) also applied the procedure in an attempt to re-evaluate the till fabrics obtained from the cross-valley moraines in the Isortoq Valley, Baffin Island (Andrews and Smithson 1966). A total of 82 fabrics were "re-analysed" and the results taken to imply that one process only was responsible for the formation of all cross-valley moraine types (linear, hooked, S-shaped and asymmetric: cf. Barnett and Holdsworth 1974). Mills (1977b) also used the technique to evaluate till fabrics sampled from valley glacier lodgement tills in the USA and Canada.

Discussion of the application of the eigenvalue technique to till fabric analysis.

In terms of statistical assumptions, the eigenvalue procedure is more applicable to the analysis of till fabric data in that it is specifically designed for the treatment of non-directed axes. However, the approach is only valid if the data are known to be unimodal, and their distribution symmetrical about the axial mode (see Figure 11.6). Spurious results may be obtained if the eigenvalue procedure is used on data that are bi- or multimodal in their

distribution. This point is well shown in Figure 11.7 where three till fabrics sampled from the cross-valley ridges in the Carsphairn area are displayed, one with a unimodal distribution, one bimodal and one multimodal.

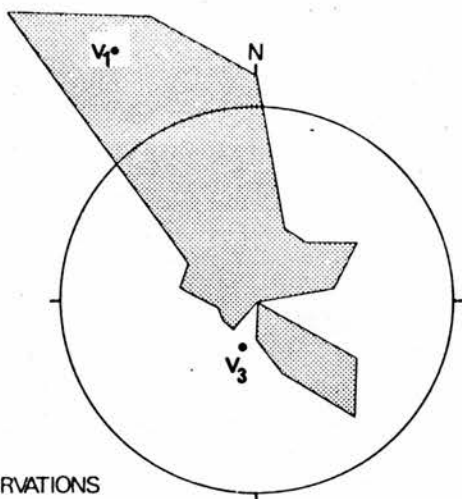
Figure 11.7(a) shows a unimodal fabric and the position of the maximum eigenvector (V_1) in relation to the primary mode. Significance levels are given below as obtained from the tables provided by Anderson and Stephens (1971), along with the $L\%$ value from the Rayleigh test (Curry 1956) and the A_n value (Stephens 1969, and see below) of the fabric. In each test on fabric (a) values of significance exceed the 0.05 level, indicating a significant departure from a uniform distribution. In this case, the maximum eigenvector accurately identifies the position of the preferred trend and the S_1 value its strength.

Fabric (b) (Figure 11.7(b)) shows a well-developed bimodal distribution, the two modes lying 30° apart. However, the maximum eigenvector occupies an intermediate position between the two modes; this is unsatisfactory if the major trend in the fabric requires identification.

Similar complications arise with multimodal fabrics. In fabric (c) two major modes (at 40° and 270°) and four minor modes are present (Figure 11.7(c)), but the position of the maximum eigenvector lies in an area containing no modal peak. Moreover, the results from the $L\%$ and the A_n tests on the fabric suggest that the distribution is not significantly different from a random or a uniform distribution, while a value significant at the 0.01 level is obtained when the maximum (S_1) and minimum (S_3) eigenvalues are tested against

Figure 11.7 Three-dimensional till fabric diagrams showing
results of percentage vector magnitude ($L\%$),
An statistic and eigenvalue (S_1 and S_3) tests.

a



$L\% = 36.6^*$
 $An_{180} = 1.3286^*$
 $An_{360} = 1.4212^*$
 $S_1 = 0.628^*$ v_1 TREND 322° PLUNGE 12°
 $S_3 = 0.088^*$ v_3 TREND 195° PLUNGE 74°

CIRCLE INDICATES 10% OF OBSERVATIONS

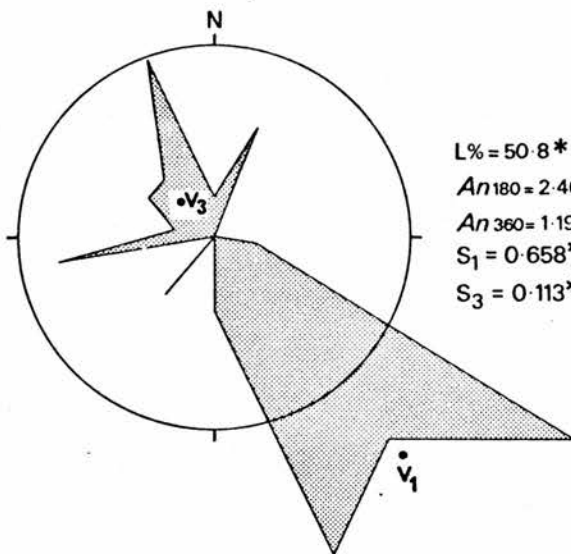
* SIGNIFICANT AT 0.01 LEVEL

|NS| NOT SIGNIFICANT

$n = 50$ PEBBLES

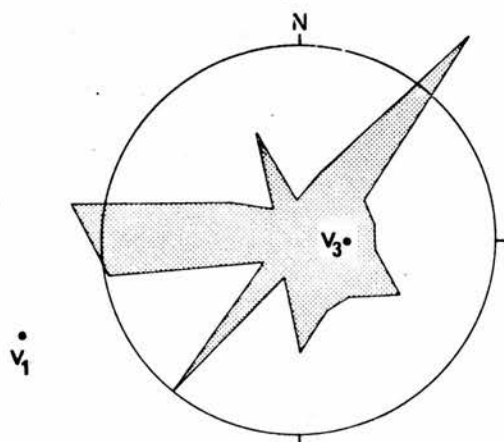
CLASS INTERVAL = 20°

b



$L\% = 50.8^*$
 $An_{180} = 2.4661^*$
 $An_{360} = 1.1958^*$
 $S_1 = 0.658^*$ v_1 TREND 140° PLUNGE 10°
 $S_3 = 0.113^*$ v_3 TREND 317° PLUNGE 80°

c



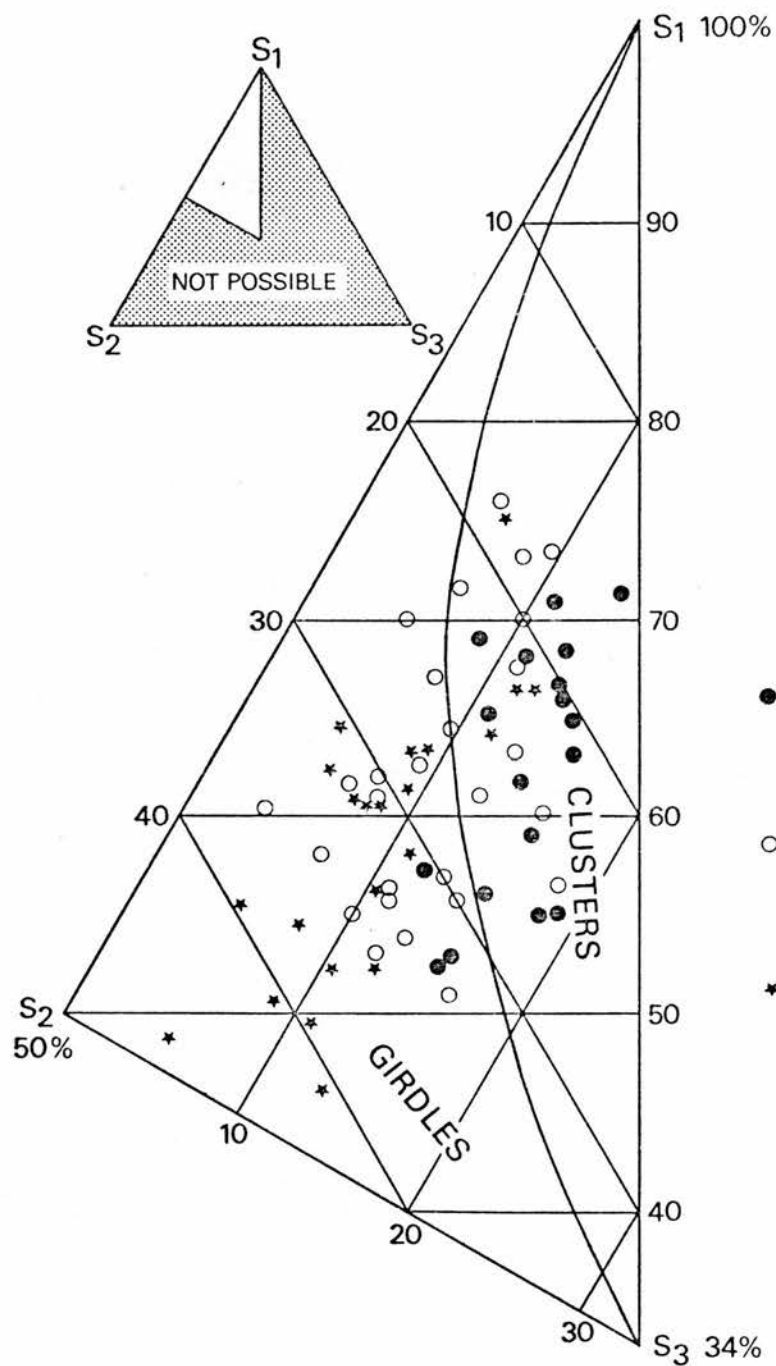
$L\% = 19.35$ |NS|
 $An_{180} = 0.3434$ |NS|
 $An_{360} = 0.1167$ |NS|
 $S_1 = 0.526^*$ v_1 TREND 252° PLUNGE 3°
 $S_3 = 0.078^*$ v_3 TREND 90° PLUNGE 87°

the tables provided by Anderson and Stephens (1971). Although this latter result does not indicate the presence of a preferred trend in the fabric, the results are confusing, especially when compared with those obtained from the L^2 and An tests.

Further, confusion may also arise in the interpretation of the results obtained from the eigenvalue analysis. For example, Mark (1974, p.104) has suggested that if the results of the eigenvalue analysis are plotted on a ternary diagram then "fabrics from different sedimentary environments or geographical areas may tend to cluster in different parts (of the diagram)". In an attempt to demonstrate this differentiation, the results of the analysis of tills taken from three different areas, each with a different depositional environment, were plotted on a ternary diagram (Figure 11.8). Ignoring any statistical assumptions that may have been transgressed in the calculation of the eigenvalues, no clear differentiation between clusters of the three till types is observable. Moreover, Mark has misapplied this particular graphical technique in that the diagram was devised to quantify fabric shape, not the depositional or geographical characteristics of the deposit from which the fabric was analysed (cf. Woodcock 1977).

It may therefore be concluded that while the eigenvalue method can produce accurate results when carefully applied to unimodal distributions that are symmetrical about the mean axis, it is not advisable to use it indiscriminately. Although the eigenvalue method is robust enough to ignore the presence of minor secondary modes in a fabric that is otherwise unimodal (e.g. Figure 11.7(a)), it is recommended that its application to strongly bimodal or

Figure 11.8 Ternary diagram illustrating eigenvalue results of till fabrics sampled from three areas and deposited in three different glacial environments.



- Fabrics from "cross-valley moraines," Isortoq Valley, Baffin Island, N.W.T. (Mark & Andrews, 1975) n = 18
- Fabrics from Sumas Till, British Columbia, Canada (Mark, 1974) n = 28
- ★ Fabrics from cross-valley ridges, Carsphairn area, west-central Southern Uplands, Scotland. n = 22

multimodal fabrics be avoided, for the results are likely to be misleading. It is essential that basic graphical (e.g. histogram plots or polar net projections) and statistical (e.g. $L\%$ and A_n statistic) procedures be carried out on the data as an initial step, in order to determine whether more detailed numerical analysis is in fact useful as well as applicable.

11.2.4 Discussion of the statistical techniques employed in till fabric analysis.

The discussions presented above indicate that two major problems beset the analysis and interpretation of till fabric data. First, as pointed out by Hill (1969), one of the most important limitations on the analysis of orientation data is the difficulty in finding suitable statistical methods for their analysis. Thus the results obtained will only be as sound as the assumptions on which the statistical techniques are based. This is a fundamental point, for it demonstrates that the most important part of any analysis of till fabric data should precede the application of the statistical techniques (cf. Watson 1966). The linear transformation, two-dimensional vector, Tukey chi-square, three-dimensional vector and eigenvector techniques considered in this paper are all designed to be used with unimodal data, and yet most till fabrics possess either bimodal or multimodal distributions. The existence of more than one mode in a fabric therefore vitiates its analysis by these methods. This is particularly the case with three-dimensional techniques, for the provision of a single estimate of the mean trend in such multimodal data yields an intermediate value that fails to define any of the modal peaks in the fabric. Moreover, as has been shown above,

the significance of fabric distributions or the values for between- and within-site fabric variability calculated from multimodal data will also be meaningless. Thus the problem is not, as Andrews and Smith (1970, p.517) suggest, "more connected with the nature of the raw data than with the misapplication of statistics", but with making sure that the data are applicable to analysis by the statistical methods available.

A second major problem concerns our lack of knowledge of the processes of till deposition and the mechanisms whereby clasts become orientated both during and after deposition. Although the theoretical aspects of these problems have been advanced in recent years (Lindsay 1970; Boulton 1971, 1975a) the mechanics are still not fully understood. Similarly, the accuracy of till fabric data collection has remained largely unaltered despite the increase in sophistication of their analysis.

These fundamental problems suggest that the application of complex, computer-based, three-dimensional procedures to the analysis of till fabric data is at best questionable. Moreover, manipulation of the data by rotation in order to enhance the primary mode of any fabric (e.g. Andrews and Shimizu 1966; Andrews and Smith 1970; Mark 1971) can lead to suspect or erroneous correlations being made with the conditions and environments of till deposition. The application of these procedures can, and has, also led to over-interpretation of fabric data. For example Roberts and Mark (1970) inferred the flow lines of former valley glaciers in the Fraser Valley, British Columbia using trend surface techniques based solely on till fabrics sampled at only 19 sites. The resultant flow lines,

however, were largely opposite to those inferred by Armstrong *et al.* (1971), who based their conclusions on glacial erratics and other evidence. In the same paper Roberts and Mark also generated flow lines, on the criteria of erratic content and till fabrics (using data from Baden Powell (1948) and West and Donner (1956)), of the Lowestoft (Anglian) and "Gipping" (Wolstonian) tills in East Anglia, suggesting that their results confirmed the presence of two tills from separate glaciations and different provenances. More recent work, however, based on detailed analysis of borehole data, particle-size, heavy minerals and stone counts indicates that both tills were deposited during the Lowestoft Glaciation and that the source area for these deposits was the bed of the North Sea (Bristow and Cox 1973; Perrin *et al.* 1973).

Various other examples are also present in the literature: cf. Harris (1967) and the discussion of his till fabric results by Straw (1968).

To help overcome these basic problems, it is suggested that a measure of fabric strength is probably a more useful criterion for analysing till fabric data, rather than attempting to calculate the mean trend. Two measures of fabric strength have been investigated by the present writer:

- (a) a modified version of the chi-square test;
- (b) two versions of the A_n statistic of Ajne (1968) and Stephens (1969) as applied to the analysis of orientation data by Dale and Ballantyne (*in press*).

The modified chi-square test

The serious problem regarding the subjectivity involved in selecting a point of origin for the division of a circular

distribution into one that is linear has already been outlined in some detail. To overcome this limitation, the χ^2 value for every possible point of origin was calculated, given the accuracy to which the orientation measurements were taken in the field ($\pm 5^\circ$ in the present study). Each cell effectively occupies 40° of arc on the circle in the form of two diametrically opposite sectors, each of 20° ; in other words, for example, 0° to $19^\circ + 180^\circ$ to 199° corresponds to one 40° sector. As such, for orientation measurements made to the nearest degree, 20 different groupings of points are possible and hence up to 20 different χ^2 values may be calculated. For measurements made to the nearest 5° , however, only four ($20/5$) groupings of points are possible, and up to four different χ^2 values will result.

In an attempt to express these data in a meaningful form for each fabric, various solutions were considered. The first two solutions concerned the use of the maximum (χ^2_{max}) and minimum (χ^2_{min}) χ^2 values calculated. However, this was often found to lead to too liberal or too conservative a test. Moreover, as the probability distributions of the maximum and minimum chi-square statistics are unknown, the values of χ^2_{max} and χ^2_{min} that lead to the rejection of the null hypothesis cannot be determined. These values were therefore not considered satisfactory in representing the distributions of calculated χ^2 values. A measure of central tendency, using the mean and median, was considered as a further solution, but this was found to be unrepresentative owing to the strongly skewed, and at times, multimodal nature of the distribution of the calculated χ^2 values. Thus the only suitable solution appears to be the adoption of a different statistic and one such is considered below.

The A_n statistic.

The A_n statistic, developed by Ajne (1968) and Stephens (1969), has been shown to provide a more satisfactory alternative for the analysis of orientation data (Dale and Ballantyne, in press). The statistic is employed to test a fabric for its departure from a uniform distribution over the 360° range of a circle (A_{n360} statistic) as well as over 180° (A_{n180} statistic): in the latter case the orientation of individual particles is analysed without regard to their dip. Results are compared with tables of significance provided by Stephens (1969). Evaluation of these statistics provides two values, which when used in conjunction can help determine the importance of "sense" in a set of till fabric measurements. Thus for any sample where both A_n values are high, both trend and plunge of the fabric may be inferred to be significantly different from a uniform distribution. A high A_{n360} value, but a low A_{n180} value suggests that the plunge of the fabric alone may be important, while a low A_{n360} and a high A_{n180} value implies that only the trend may be significant (Dale and Ballantyne, in press).

The A_n statistic possesses two major advantages in that, first, the results are calculated independently of any *a priori* point of origin, and secondly, that the tests do not assume a circular-normal distribution in the data. These are fundamental advantages that overcome many of the limitations, mentioned previously, concerning the statistical tests currently employed in the analysis of till fabric data. Thus in Section 11.3 the A_n statistic will be used as the basic statistic in the analysis of the till fabrics sampled from the cross-valley ridges.

11.2.5. Conclusions

It is recommended that, regardless of the purpose for which till fabrics are being employed, they should be used in combination with other methods of analysis (e.g. morphological mapping, particle-size analysis, heavy mineral analysis, lithological analysis of clasts in the till, roundness and shape analysis of clasts) that may be considered applicable. This holistic approach should provide sufficient evidence from which realistic conclusions may be drawn, thus avoiding the pitfalls outlined above.

Secondly, the statistical assumptions underlying any technique as applied to the analysis of orientation data must be adhered to when considering the applicability of each step in the procedure. The importance of this point was emphasised by Pincus as early as 1953 and reinforced by Watson (1966). Pincus recognised that the "peculiarities of orientation data require a special category of models and tests, which have to be applied with considerable efficiency within the range of uses for which they have been intended" (1953, p.508). It is unfortunate that this warning has not subsequently been heeded by some research workers.

Thirdly, the precision of the results is largely a reflection of the accuracy with which the data have been collected, rather than the complexity with which they are analysed. Thus the call for the development of even more complex models to analyse multimodal fabrics (Jones and James 1968; Ramsden 1970; Andrews 1971b) would seem to be a plea for statistical "overkill". It has been shown above that the most sophisticated techniques devised so far have led to confusion and over-interpretation rather than clarity and elucidation.

Fourthly, the basic procedures of graphical representation (see Andrews and Smith (1970) and Andrews (1971a) for reviews of these techniques) of till fabric data as opposed to the presentation of tables of statistical significance are essential in that:

- (a) graphical procedures provide a common "language" for the examination of fabrics irrespective of the statistical analysis employed and ensure that a publication will not become entirely worthless if the statistical methods used in it are shown to be invalid;
- (b) the graphical representation of till fabric data possesses certain advantages in that the diagrams are heuristically intelligible, they enable the presence of bimodality and multimodality in the data to be easily identified and provide a visual indication of the spread of the data (Watson 1966; Ramsden 1970; McSaveney 1971; Marcussen 1975). These advantages also assist in deciding the correct numerical techniques, if any, that may be used in the analysis of the data.

In view of the discussion presented above, it is concluded that till fabric data should be analysed using graphical techniques (rose diagrams or contoured polar diagrams) in combination with simple statistics that determine the strength of the trend in any fabric: the present study has shown that the A_n statistic is the most effective of the currently used techniques for this analysis. Further, it is advocated that more sophisticated techniques should only be used when the data satisfy the appropriate statistical assumptions and when the methodology of the research programme requires them.

11.3 TILL MACRO-FABRIC ANALYSIS RESULTS ON THE CROSS-VALLEY RIDGES OF THE CARSPHAIRN AREA

11.3.1 Introduction

Till macro-fabric analysis was carried out at 36 sites in 16 of the cross-valley ridges in the Carsphairn area using the procedures and sampling design outlined in Chapter 3. Till fabric analysis was also attempted in the ridges located in the Garryhorn Valley. However, owing to the effect of magnetic anomalies associated with the lead and silver mineralisation in this area, the results were found to be erroneous and will not therefore be considered further. Five till fabrics measured from valley-fill deposits have been described elsewhere (Chapter 7, section (iii)).

11.3.2 Results and analysis of the till fabric data.

In order to bring out any preferred trends in the data, the fabrics were drawn as three-dimensional rose diagrams, observations being grouped into $18 \times 20^\circ$ units (Figures 11.9 to 11.12). The relative number of stones in each grouping can be judged by the radial circles, which indicate 10% and 20% of observations for the inner and outer circles respectively. The diagrams also show each rose diagram in relation to:

- (a) its position within surveyed cross-profiles of the cross-valley ridges;
- (b) its position with respect to the direction of former ice movement, the latter being determined from the orientation of striae, ice-moulded landforms and glacial erratics trains.

Figure 11.13 shows till fabrics measured from ridges where only one

Figure 11.9 Three-dimensional till fabric diagrams from the cross-valley ridges, showing the position of the sampling sites.

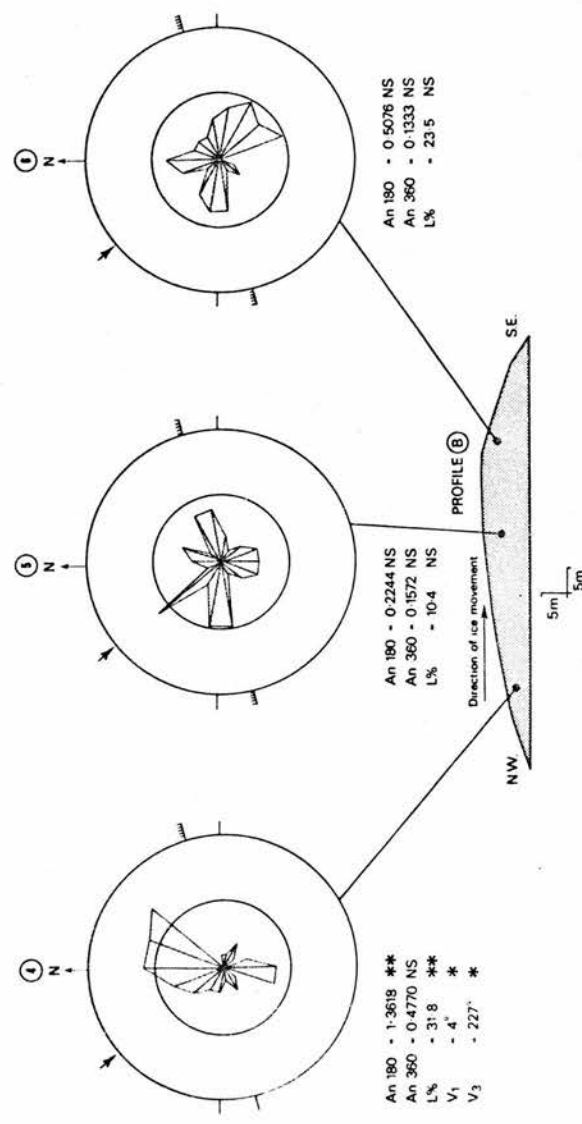
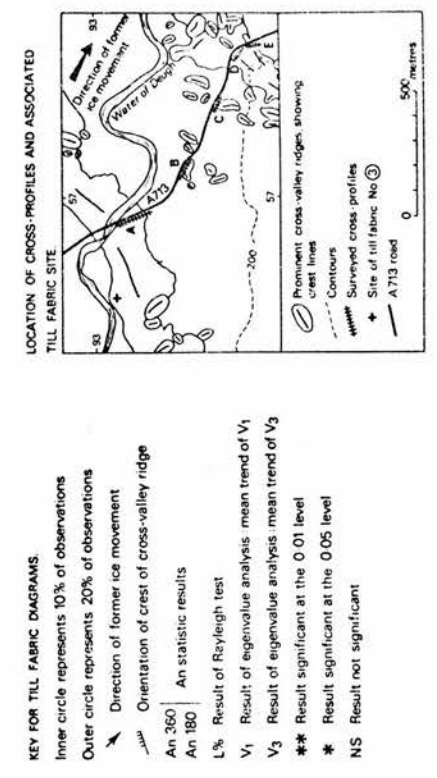
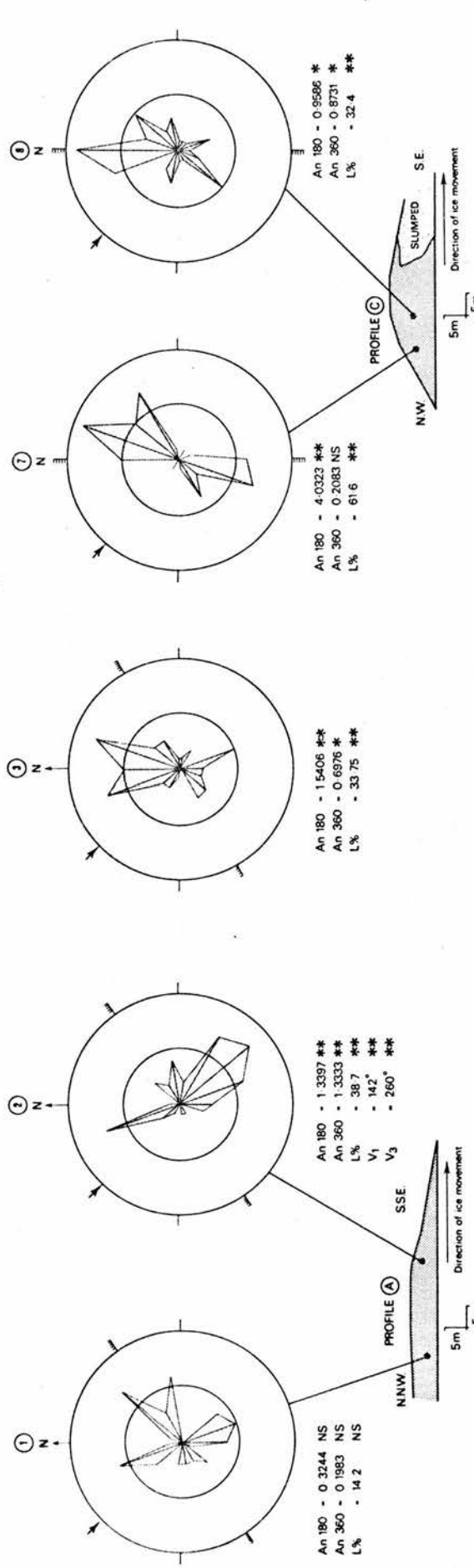


Figure 11.10 Three-dimensional till fabric diagrams from the cross-valley ridges, showing the position of the sampling sites. Key as for Figure 11.9.

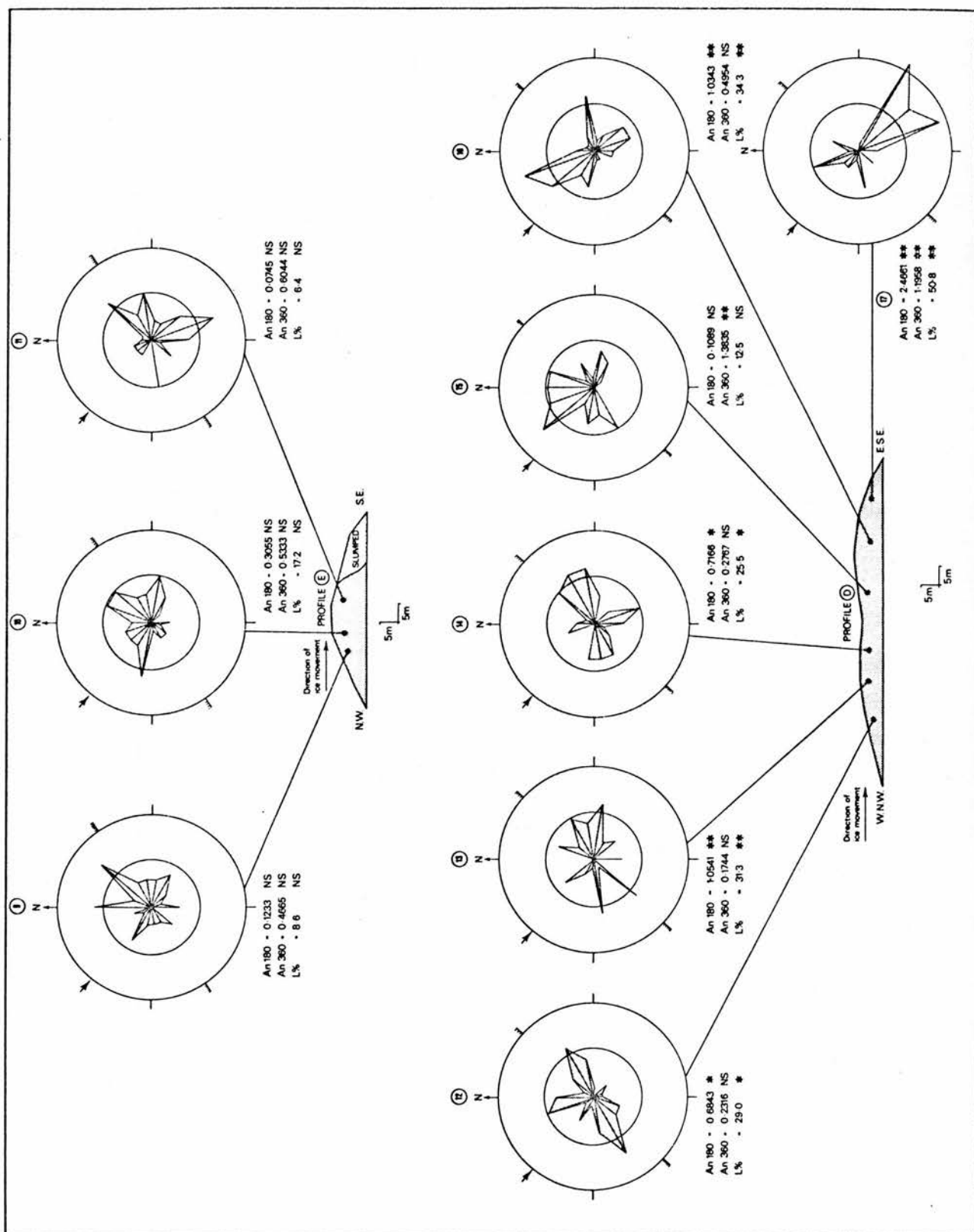
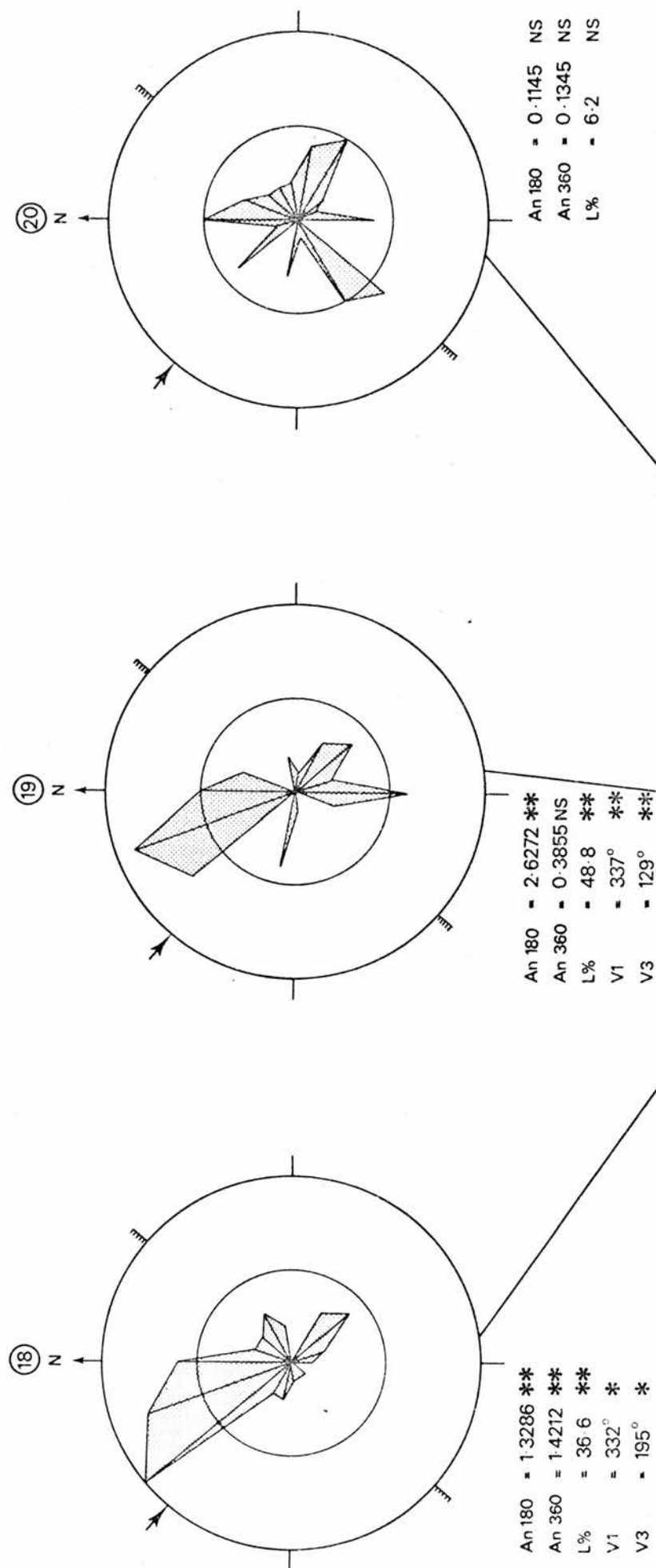


Figure 11.11 Three-dimensional till fabric diagrams from the cross-valley ridges, showing the position of the sampling sites. Key as for Figure 11.9.



Direction of
ice movement

PROFILE (E)

5m
5m

Cross-valley ridge by Dalshangan House
NX 598885

Figure 11.12 Three-dimensional till fabric diagrams from the cross-valley ridges, showing the position of the sampling sites. Key as for Figure 11.9.

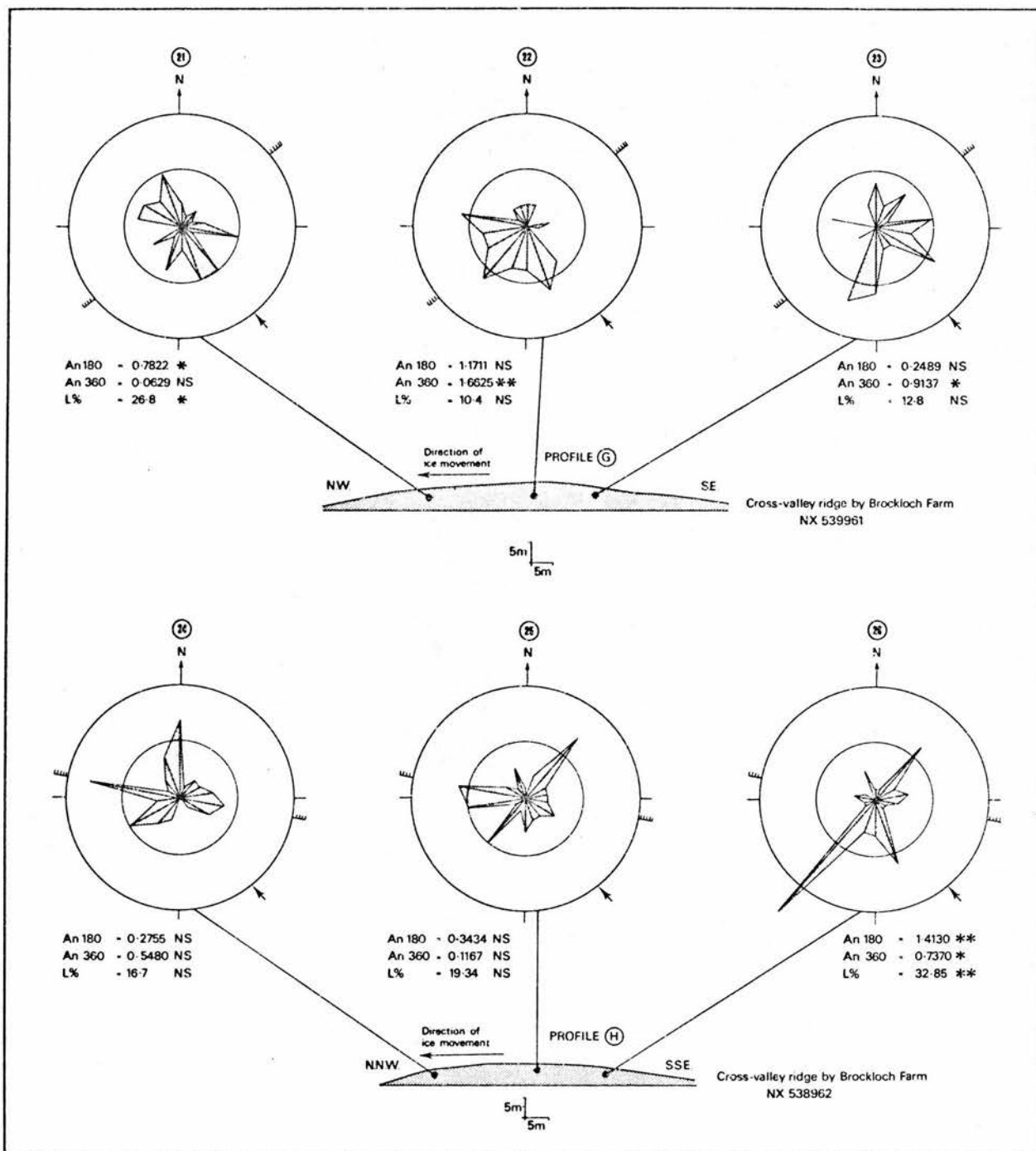
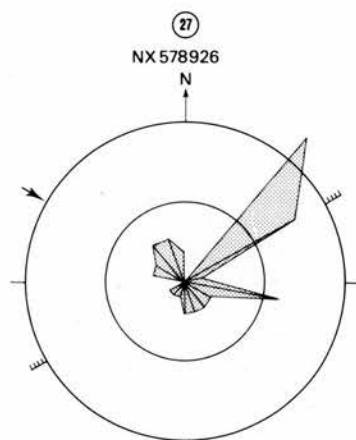
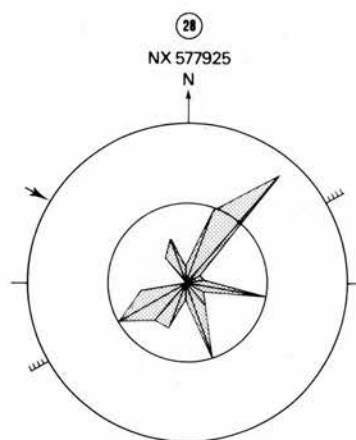


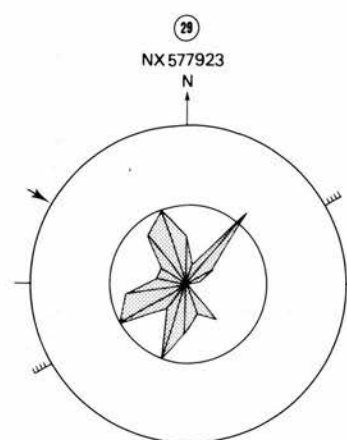
Figure 11.13 Three-dimensional till fabric diagrams from the
cross-valley ridges. Key as for Figure 11.9.



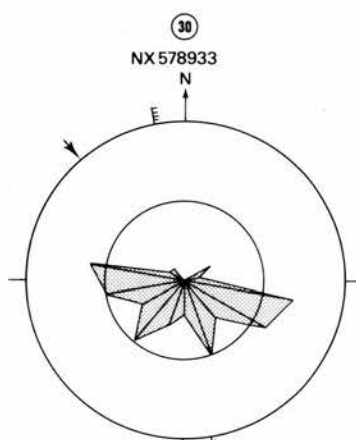
An 180 = 0.3033 NS
An 360 = 1.9067 **
L% = 13.26 NS



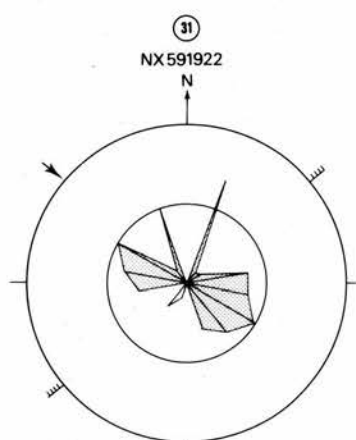
An 180 = 0.7643 *
An 360 = 0.1828 NS
L% = 22.9 NS



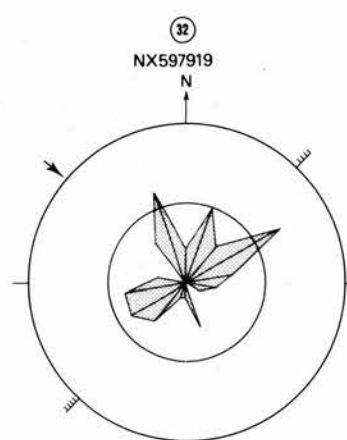
An 180 = 0.3733 NS
An 360 = 0.4917 NS
L% = 18.1 NS



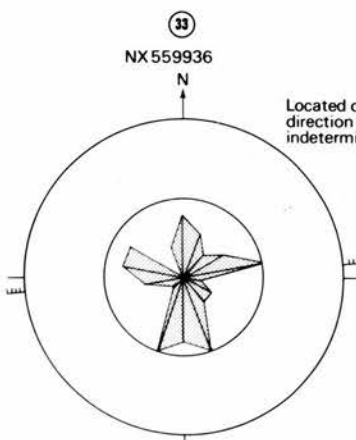
An 180 = 1.0297 **
An 360 = 1.2686 **
L% = 26.0 *
V₁ = 95° *
V₂ = 3° *



An 180 = 0.6155 NS
An 360 = 0.2161 NS
L% = 23.7 NS

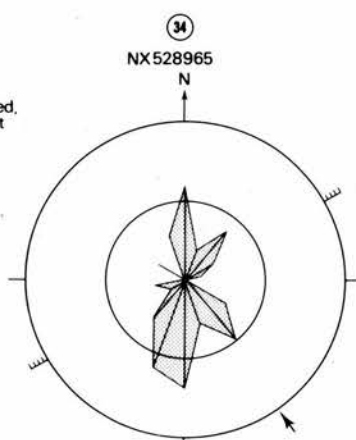


An 180 = 0.5754 NS
An 360 = 0.6083 NS
L% = 22.5 NS

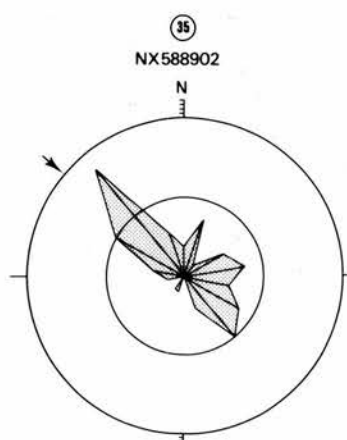


Located on former ice-shed,
direction of ice movement
indeterminable

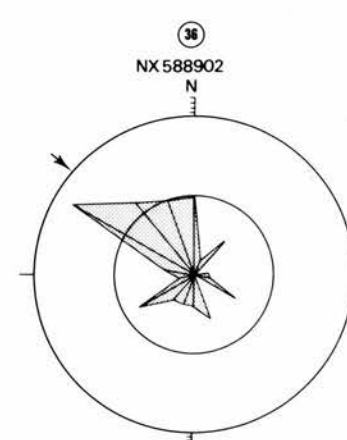
An 180 = 0.1533 NS
An 360 = 0.1161 NS
L% = 9.2 NS



An 180 = 1.4020 **
An 360 = 0.3072 NS
L% = 36.6 **
V₁ = 185° **
V₃ = 333° **



An 180 = 1.3242 **
An 360 = 0.5847 NS
L% = 35.2 **
V₁ = 305° **
V₃ = 209° **



An 180 = 0.7666 *
An 360 = 1.2746 **
L% = 26.7 *

or two exposures were sampled; National Grid reference numbers give the exact location of the sites and the cross-profiles of the ridges are omitted. The results of the An and the $L\%$ tests carried out on each fabric are presented beneath each diagram. Where the fabric data satisfy the assumptions of the eigenvalue procedure, then the V_1 and V_3 results (with their corresponding significance values: S_1 and S_3) are also incorporated on the diagram.

As a first step in the analysis of the till fabric data the An_{180} and An_{360} statistics were used in conjunction with visual inspection of the rose diagrams in order to determine those fabrics that satisfied the statistical assumptions of the eigenvalue procedure (viz: a unimodal distribution, symmetrical about the mean axis). The results of the An_{180} and An_{360} analysis are shown in Table 11.1. Eight of the 36 fabrics analysed (fabrics (2)(3)(8)(17)(18)(26)(30)(36)) had distributions that were significantly different from a uniform one in both An_{180} and An_{360} , suggesting that both the trend and plunge of the fabric were significant. However, visual inspection of these fabrics (Figures 11.9 to 11.13) shows that five possess bimodal or multimodal distributions. Similarly, of the 11 fabrics that had significant An_{180} values only (and therefore inferred significant trends) four were unimodally distributed (fabrics (4)(19)(34)(35)), two were bimodal ((16)(17)) and six multimodal (fabrics (12)(13)(14)(21)(28)). The four fabrics with significant An_{360} values only (and therefore inferred significant plunges) all showed multimodal distributions on visual inspection.

Thus the seven fabrics that showed unimodal distributions were further analysed using the eigenvalue procedure and these results are

Table 11.1 Results of the A_n statistical test on till fabrics
measured from the cross-valley ridges by Carsphairn.

Till fabric number	A_{n180} value	Significance* level	A_{n360} value	Significance* level
1	0.3244	NS	0.1983	NS
2	1.3397	0.01	1.3333	0.01
3	1.5406	0.01	0.6976	0.05
4	1.3618	0.01	0.4770	NS
5	0.2244	NS	1.1572	NS
6	0.5076	NS	0.1333	NS
7	4.0323	0.01	0.2083	NS
8	0.9586	0.05	0.8731	0.05
9	0.1233	NS	0.4665	NS
10	0.3055	NS	0.5333	NS
11	0.0745	NS	0.6044	NS
12	0.6843	0.05	0.2316	NS
13	1.0541	0.01	0.1744	NS
14	0.7166	0.05	0.2767	NS
15	0.1089	NS	1.3835	0.01
16	1.0343	0.01	0.4954	NS
17	2.4661	0.01	1.1958	0.01
18	1.3286	0.01	1.4212	0.01
19	2.6272	0.01	0.3855	NS
20	0.1145	NS	0.1345	NS
21	0.7822	0.05	0.0629	NS
22	0.1711	NS	1.6625	0.01
23	0.2489	NS	0.9137	0.05
24	0.2755	NS	0.5480	NS
25	0.3434	NS	0.1167	NS
26	1.4130	0.01	0.7370	0.05
27	0.3033	NS	1.9607	0.01
28	0.7643	0.05	0.1828	NS
29	0.3733	NS	0.4917	NS
30	1.0297	0.01	1.2686	0.01
31	0.6155	NS	0.2161	NS
32	0.5754	NS	0.6083	NS
33	0.1533	NS	0.1181	NS
34	1.4020	0.01	0.3072	NS
35	1.3242	0.01	0.5847	NS
36	0.7666	0.05	1.2746	0.01

Number of fabrics analysed = 36
 Number of fabrics where both trend and plunge are significant = 8
 Number of fabrics where trend alone is significant = 11
 Number of fabrics where plunge alone is significant = 4
 Number of fabrics with no significant departure from uniformity = 13

* Values exceeding 0.969 significant from a uniform distribution at the 0.01 level, those exceeding 0.653 are significant at the 0.05 level (after Stephens 1969).

presented in Table 11.2. In the table column 1 shows the fabric number, which corresponds to the fabrics depicted in Figures 11.9 to 11.13; column 2 gives the mean trend of the fabric as calculated by the eigenvalue procedure (V_1); and column 3 gives the low plunge values of V_1 . The S_1 values and their significance levels are shown in columns 4 and 5 respectively, high values for S_1 indicating strong clustering of the data. (Values exceeding 0.484 indicate that the data are significantly different from a random distribution drawn from a uniform population at the 0.01 level, while those exceeding 0.460 are significant at the 0.05 level for $n = 50$ (Anderson and Stephens 1971).) Columns 6 and 7 present the trend and plunge of the V_3 values, which is the pole to the preferred plane of V_1 . As the plunge of the V_3 values tends to be steep (over 66° in this study), then the plunge of the V_1 planes tends to be low (less than 12° in this study). Columns 8 and 9 show the S_3 values and their respective levels of significance; low values for S_3 indicate strong clustering. (Values smaller than 0.198 being significant at the 0.01 level and values less than 0.216 significant at the 0.05 level for $n = 50$ (Anderson and Stephens 1971).) Column 10 presents the direction of former ice movement, based on the orientation of striae, ice-moulded landforms and glacial erratics trains, the first figure representing the point of the compass from which the ice advanced, and column 11 the orientation of the long axis of the cross-valley ridge from which the fabric was measured.

These results are considered to give an accurate interpretation of the mean trend and strength of the fabrics concerned. As an experiment, the remaining 29 sets of data were run using Mark's (1973)

Table 11.2 Results of the analysis of unimodal till fabrics using the eigenvalue procedure.

1	2	3	4	5	6	7	8	9	10	11
Till fabric number	Mean trend (degrees) V_1	Plunge (degrees) V_1	S_1	Signi- ficance level	Mean trend (degrees) V_3	Plunge (degrees) V_3	S_3	Signi- ficance level	Direction of former ice movement (degrees)	Ridge orientation (degrees)
2	142	12	0.61	0.01	260	67	0.093	0.01	315° to 135°	55° - 235°
4	4	4	0.627	0.01	227	65	0.088	0.01	320° to 140°	75° - 225°
18	332	12	0.628	0.01	195	74	0.088	0.01	310° to 130°	40° - 220°
19	337	9	0.66	0.01	128	80	0.119	0.01	310° to 130°	40° - 220°
30	95	1	0.55	0.01	3	68	0.095	0.01	320° to 140°	170° - 350°
34	185	5	0.637	0.01	333	85	0.07	0.01	145° to 325°	60° - 240°
35	305	2	0.606	0.01	209	65	0.084	0.01	310° to 130°	0° - 180°

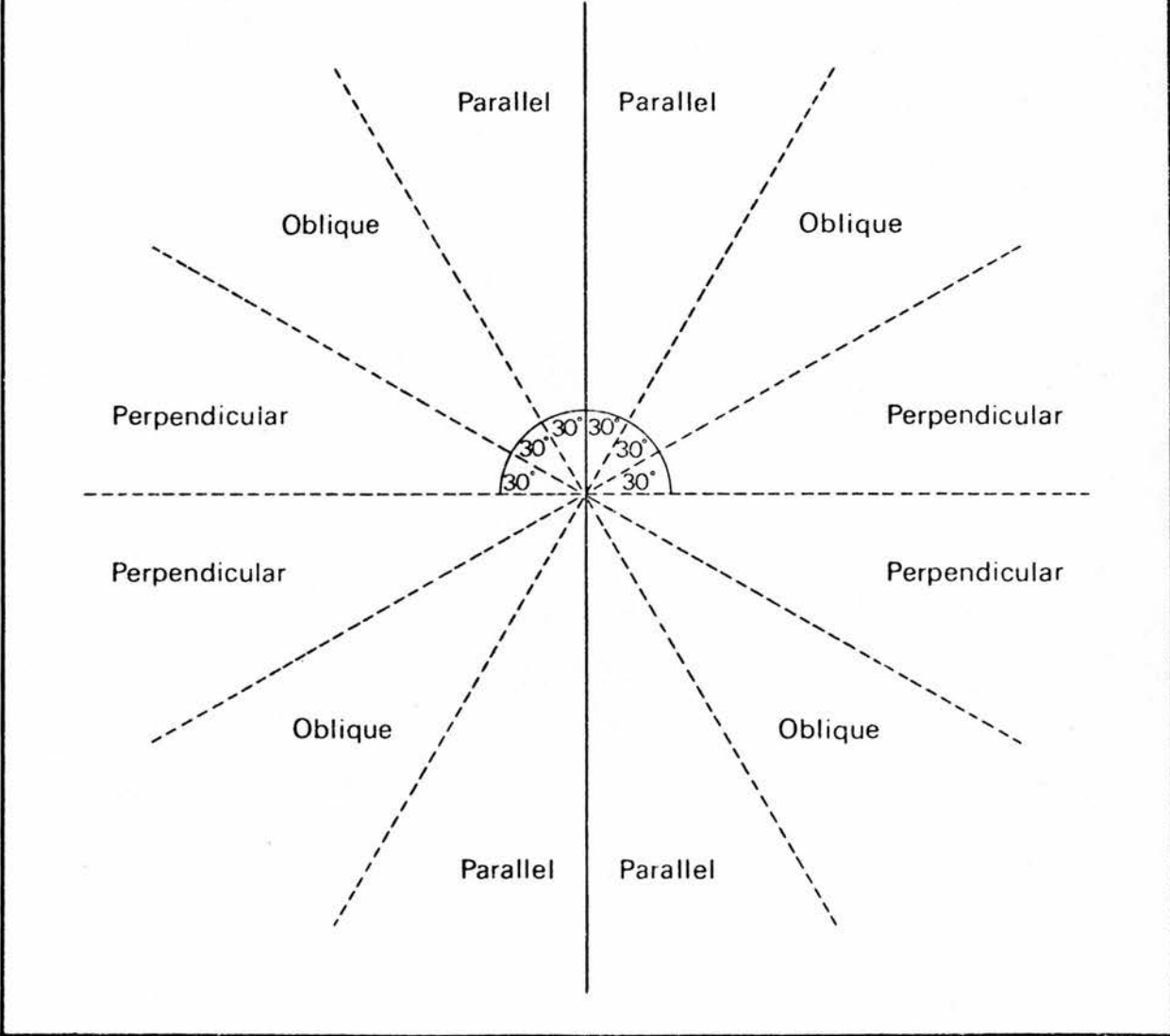
eigenvalue program and 28 of these were found to possess V_1 and V_3 trends significant at the 0.01 level, while the remaining fabric was significant at the 0.05 level. Thus the caution argued for above in connection with the indiscriminate application of the procedure to any fabric distribution is certainly well illustrated, for it seems that the technique produces mean trends at high levels of significance even when the λ_n values suggest that no departure from a uniform distribution exists.

Before considering the relationships between the till fabrics, the orientation of the ridges and the direction of former ice movement it is necessary to define certain terms. The literature on the analysis of till fabrics sampled from moraines reveals numerous terms describing qualitatively the attitude of the fabric maxima to moraine-crest orientation. Such adjectives as "transverse", "discordant" or "across" are imprecise. Thus it was decided to adopt a series of arbitrary categories that would specifically define the possible relationships. Figure 11.14 shows a schematic diagram with the ridge axis orientated 0° to 180° . Within any 90° sector measured from the crest of this ridge, a fabric whose mean trend lay between 0° and 30° was defined as being parallel to the crest. Mean fabric trends lying between 31° and 60° of arc were oblique to the crest and those between 61° and 90° perpendicular.

Using these categories and comparing the values in columns 2 and 11 in Table 11.2, certain relationships are observable. Of the seven unimodal fabrics, five (fabrics (2)(4)(18)(19)(30)) show a mean trend perpendicular to the ridge axis, while the remainder (fabrics (34)(35)) are orientated oblique to it. Further, in all these seven samples the

Figure 11.14 Schematic diagram showing the relationship
between categories of pebble orientation and
cross-valley ridge crest alignment.

Orientation of
Ridge Crest



angle between the mean fabric trend and the ridge orientation falls between 55° and 87° . There also seems to be a relationship between mean fabric trend and direction of former ice movement in the area. Four of the fabrics ((2)(18)(19)(35)) possess mean trends parallel to ice flow, while the other three are oblique to it.

Although the small sample size restricts any general inferences that may be drawn from these data, the two relationships tend to suggest that a complex of interacting factors was responsible for the fabric patterns, which involved both the ridge-forming processes and shear stresses applied by ice movement. Similar suggestions were made by Cowan (1968) and Lundqvist (1969b) who were working on ribbed and Rogen moraines respectively.

Comparison of the data in Table 11.2 with their location in the Carsphairn area and the position from which they were sampled in the ridge (i.e. proximal, distal or centre) shows no significant correlations or preferred clustering. The geographical location of the unimodal fabrics is variable, occurring in ridges close to the former ice-divide as well as up to 5 km from it. The sampling position of the fabrics within the ridges shows that three fabrics were sampled from proximal limbs, two from distal limbs and two from the central parts.

Although the statistical analysis of the remaining 29 fabrics does not seem to provide any consistent results, the relationships between pebble orientation, cross-valley ridge alignment and direction of former ice movement were evaluated in two ways.

- 1) The fabric diagrams (Figures 11.9 to 11.13) were interpreted qualitatively, drawing on examples that illustrated any of the above-

mentioned relationships. As part of this analysis included a consideration of "primary" and/or "major" (the two terms being used synonymously in this case) modes in the fabrics, it was found necessary to define these terms. An arbitrary value has been selected for the definition of a "primary" or a "major" mode, this being where the number of measured pebbles in any one 20° sector exceeded 10 per cent of the total observations ($n = 50$).

Inspection of the fabric diagrams showed that of the 16 ridges within which at least one till fabric was measured ten were orientated perpendicular to the direction of former ice flow, four at an oblique angle and one parallel (Table 11.3). At one location (Lagwine ridge: NX 559936, fabric 33) the ridge is situated so close to the former ice-shed that the direction of former ice movement could not be determined.

Of the 36 till fabrics measured, seven showed one primary mode parallel to the direction of ice movement (fabrics (2)(16)(17)(18)(19)(35) and (36)), four were oblique to it (fabrics (4)(8)(30)(34)) and six perpendicular (fabrics (7)(12)(14)(26)(27)(28)). These fabrics showed no preferred clustering in terms of either their proximity to the former ice-divide or the position from within the cross-valley ridges in which they were sampled. The remaining 19 were considered so variable that no specific conclusions could be drawn concerning their relationship to former ice movement.

Analysis of the relationship between the primary modes of the fabrics and ridge crest orientations showed that 11 of the 36 fabrics were markedly discordant to the ridge axis, six being perpendicular to the crest (fabrics (2)(4)(17)(18)(19)(30)) and five oblique

Table 11.3 The relationship between cross-valley ridge orientation and the direction of former ice movement in the Carsphairn area.

Grid reference of cross-valley ridge and till fabric numbers from each ridge		Orientation of crest of cross-valley ridge	Direction of former ice movement	Relationship between ridge orientation and ice movement
1	NX 568928	55° to 235°	315° to 135°	perpendicular
2				
3				
4	NX 570927	75° to 255°	320° to 140°	perpendicular
5				
6				
7	NX 573926	10° to 190°	310° to 130°	oblique
8				
9	NX 576923	55° to 235°	310° to 130°	perpendicular
10				
11				
12	NX 575924	40° to 220°	310° to 130°	perpendicular
13				
14				
15	NX 576924	40° to 220°	310° to 130°	perpendicular
16				
17				
18	NX 598886	40° to 220°	310° to 130°	perpendicular
19				
20				
21	NX 539962	50° to 230°	140° to 320°	perpendicular
22				
23				
24	NX 538963	90° to 270°	140° to 320°	oblique
25				
26				
27	NX 577926	60° to 240°	300° to 120°	oblique
28				
29				
30	NX 978933	170° to 350°	320° to 140°	parallel
31	NX 591923	50° to 230°	310° to 130°	perpendicular
32	NX 597918	45° to 225°	310° to 130°	perpendicular
33	NX 559936	85° to 265°	indeterminable	indeterminable (see text)
34	NX 527966	60° to 240°	145° to 325°	perpendicular
35	NX 589901	0° to 180°	310° to 130°	oblique
36				

(fabrics (16)(26)(34)(35)(36)). The primary modes of six fabrics ((7)(8)(12)(14)(27)(28)) were parallel to the orientation of the ridge crest. Of the remaining 19 fabrics, 15 exhibited several equally well-developed primary peaks, which made their interpretation difficult. For example, fabric (13)(Figure 11.10) possesses three equally developed modes, one parallel to the trend of the ridge crest, a second perpendicular and a third at an oblique angle. The other four fabrics showed no major modes as covered by the definition on p. 286.

2) A similar procedure to that adopted for defining the attitude of mean fabric trends to the orientation of the cross-valley ridge crests (i.e. parallel, oblique or perpendicular) was employed in the analysis of individual pebble orientations measured in each till fabric. The total number of pebbles in each of the above three categories in each fabric are shown in Table 11.4. In contrast to the analysis of the fabric modes, these results show that in 17 of the 36 fabrics the greatest percentage of pebbles is orientated parallel to the crests of the cross-valley ridges (values ranging between 36 per cent and 70 per cent of the total). In six fabrics the greater percentage of pebbles is oblique to the crests (ranging between 38 per cent and 46 per cent), while 12 are predominantly perpendicular to the ridge axes (ranging between 36 per cent and 62 per cent). One result (fabric (10)) is tied between parallel and oblique, with 38 per cent in each category.

Inspection of these results indicates no preferred location of the dominant attitude of individual pebbles in terms of their position within the ridges. For example, the 12 fabrics with the greatest

Table 11.4 Percentage total of individual pebble orientations and their relationship to the alignment of the cross-valley ridge crests. Chi-square results refer to analysis of frequency totals.

Fabric number	*Position in cross-valley ridge	Orientation of ridge to direction of ice movement	parallel	oblique	perpendicular	χ^2 results
			(%)	(%)	(%)	
1	C	perpendicular	46	14	40	0.05
2	D		24	18	58	0.01
3	P		26	32	42	NS
4	P	perpendicular	16	36	48	0.05
5	C		42	32	26	NS
6	D		36	32	32	NS
7	C	oblique	70	24	6	0.01
8	P		62	22	16	0.01
9	P		40	34	26	NS
10	C	perpendicular	38	36	24	NS
11	D		44	16	40	0.05
12	P		54	30	16	0.01
13	C	perpendicular	42	32	26	NS
14	D		54	36	10	0.01
15	P		32	32	36	NS
16	C	perpendicular	24	32	44	NS
17	D		14	24	62	0.01
18	P		18	36	46	0.05
19	C	perpendicular	14	42	44	0.05
20	D		36	38	26	NS
21	D		18	36	46	0.05
22	C	perpendicular	32	38	30	NS
23	P		34	42	24	NS
24	D		44	30	26	NS
25	C	oblique	46	34	20	NS
26	P		22	48	30	NS
27	P		48	24	28	NS
28	C	oblique	44	32	24	NS
29	D		44	20	36	NS
30	D	parallel	20	38	42	NS
31	C	perpendicular	30	24	46	NS
32	C	perpendicular	48	32	20	NS
33	C	-	36	22	42	NS
34	C	perpendicular	26	44	30	NS
35	P	oblique	24	46	30	NS
36	C		40	36	24	NS

*P = proximal limb of ridge; D = distal limb of ridge; C = central part of ridge.

percentage of pebbles orientated perpendicular to the ridge crests are distributed with four fabrics in each of the proximal and distal slopes and four in the central part of the ridges. Further, there is no correlation between the dominant individual pebble orientation and the geographical location of the ridge with respect to the former ice-divide zone.

To analyse these data, the one-sample chi-square test (Norcliffe 1977) was used to compare the total frequency from each category in each sample with a uniform distribution ($E = 16.666$). The null hypothesis set up stated that there was no significant difference (at either the 0.05 or 0.01 levels) between the attitude of the dominant orientation of the pebbles (i.e. parallel, oblique or perpendicular) and the trend of the ridge crests. The results of this analysis are presented in Table 11.4; the higher the χ^2 value, the less uniformly are the pebbles distributed. Of the 36 samples analysed, 24 showed no significant difference from a uniform distribution, while 12 showed significant differences (six at the 0.01 level (fabrics (2)(7)(8)(12)(14)(17) and six at the 0.05 level (fabrics (1)(4)(11)(18)(19)(21)). The fabrics that showed significant differences were equally distributed between the perpendicular ($n = 6$) and the parallel ($n = 6$) categories; no particular part of the ridges from which the fabrics were sampled was preferred. These/therefore suggest that although in the majority of fabrics, pebbles appear to show a preferred alignment (in terms of frequency) parallel to the cross-valley ridge crests, these tend not to be statistically significant.

11.3.3 Dip analysis*

A detailed analysis of the dip patterns of the till fabrics was considered necessary as it was thought that they might provide evidence regarding formation of the cross-valley ridges. For example, Lundqvist (1949) has shown that in deposits affected by slumping or mass movement, the long axes of stones tend to lie in the direction of movement. If the cross-valley ridges were formed in a supraglacial environment or between ice walls then, with the melting of the ice, the dip of the pebbles in the proximal and distal limbs of the ridges might show signs of preferred dips paralleling the ridge slopes (cf. Boulton 1968, 1971).

Using the three arbitrary categories defined above (p.284), the mean dip of the pebbles within each of the parallel, oblique and perpendicular categories was calculated (Table 11.5). These results show an almost complete overlap in the range of mean dip values for each category. Mean dips parallel to the ridge crests vary from 10.4° to 25° (grand mean = 16.9°), those lying oblique to the crests range from 8.8° to 21° (grand mean = 16.1°), while those in the perpendicular category range from 8.3° to 28.5° (grand mean = 17.1°). This suggests that there is no consistent relationship between the mean dips of pebbles and their orientation to cross-valley ridge alignments.

* In this section, the differences in terminology used in the discussion of the statistical techniques between "plunge" and "dip" are not employed. For clarity, all measurements of pebble inclination are referred to as "dip".

Table 11.5 Mean angle of dip of individual pebbles in each orientation category.

Till fabric number	*Position in cross-valley ridge	Mean angle of dip of pebbles		
		Parallel (degrees)	Oblique (degrees)	Perpendicular (degrees)
1	C	10.4	9.3	13.5
2	D	20.0	16.7	19.1
3	P	15.4	19.1	17.4
4	P	18.8	13.6	13.5
5	C	17.9	17.2	15.8
6	D	17.2	15.0	15.9
7	C	13.9	8.8	8.3
8	P	15.0	13.2	13.1
9	P	17.3	15.9	14.6
10	C	22.9	14.5	23.3
11	D	18.2	15.6	13.3
12	P	17.2	19.3	19.4
13	C	16.9	21.0	28.5
14	D	18.5	13.6	20.0
15	P	16.9	18.1	18.1
16	C	19.2	11.9	17.3
17	D	15.7	12.9	18.5
18	P	15.6	20.8	14.8
19	C	17.8	18.3	19.3
20	D	15.3	18.9	19.2
21	D	25.0	16.9	16.1
22	C	23.0	15.3	19.0
23	P	16.2	16.4	13.3
24	D	11.8	18.0	9.6
25	C	15.6	13.2	13.0
26	P	10.9	13.8	14.3
27	P	16.7	18.8	21.8
28	C	15.7	20.3	14.6
29	D	18.6	20.0	22.5
30	D	12.5	17.6	22.1
31	C	21.0	12.1	19.3
32	C	14.2	16.6	14.5
33	C	19.2	16.8	16.2
34	C	13.8	12.7	17.3
35	P	20.8	18.3	14.0
36	C	15.5	18.3	24.6

* P = proximal limb of ridge; D = distal limb of ridge;

C = central part of ridge.

Similarly, there appears to be no obvious relationship between the mean angle of dip for the pebbles in each category of orientation and the position of the fabric within the ridges. In the proximal limbs of the ridges mean dip values range from 10.9° to 20.8° in the parallel category, between 13.2° and 20.8° in the oblique and between 13.1° and 21.8° in the perpendicular. Within the distal limbs the respective range of values is 11.6° to 25° , 12.9° to 21° , and 9.6° to 22.5° , while in the central parts of the ridges the values are 10.4° to 23° , 8.8° to 21° and 8.3° to 28.5° .

In order to test for any relationship between pebbles dipping away from the ridge crests and the angle of slope of the proximal and distal limbs of the ridges, those pebbles lying within the 60° arc perpendicular to the ridge axes and dipping away from the crest-line were analysed. These results are presented in Table 11.6 and show several interesting features.

- 1) Only a limited number of pebbles are orientated perpendicular to the ridge crest. Only in one fabric (17) do the number of pebbles exceed 50 per cent of the total observations; the remaining values vary between 6 per cent and 32 per cent.
- 2) There is a general lack of accordance between the mean slope angle of the ridges analysed and the mean angle of dip of the pebbles. This observation is supported by results from the Mann-Whitney U-test (Siegel 1956), which indicate that the difference between the two mean values in all samples is significant at the 0.01 level.

The investigation of dip patterns in further detail was not pursued owing to the above-mentioned problems concerning such unknowns

Table 11.6 Comparison between the mean angle of dip of pebbles orientated perpendicular, and dipping away from the cross-valley ridge crests and the mean slope angle of the ridges. Only paired observations from the same ridge were analysed.

Till fabric number	Position of fabric within cross-valley ridge	Number of pebbles with perpendicular orientation and dipping away from ridge crest	\bar{x} angle of dip of pebbles (degrees)	\bar{x} angle of slope of cross-valley ridges (degrees)	Results of Mann-Whitney U-test
4	proximal	14	10.0	13	0.01
6	distal	7	15.7	17	0.01
9	proximal	6	13.3	22	0.01
11	distal	15	13.0	15	0.01
12	proximal	8	17.5	11	0.01
14	distal	3	18.3	4	0.01
15	proximal	13	19.2	11	0.01
17	distal	27	21.3	16	0.01
18	proximal	16	15.9	5	0.01
20	distal	9	21.1	8	0.01
21	distal	12	13.3	9	0.01
23	proximal	10	14.0	8	0.01
24	distal	11	8.2	9	0.01
26	proximal	12	15.4	8	0.01

as the plane of deposition of the fabric. Although certain workers have advocated detailed investigations into dip patterns by using dip frequency distribution analysis (e.g. Mills 1975) this approach is considered to be a less than accurate portrayal of the particles at the time of their deposition (Holmes 1941; Young 1969).

11.3.4 Discussion of till macro-fabric results

The results of the analysis presented above show that a wide variety of fabric patterns occur in the cross-valley ridges. Certain fabrics possess several well developed primary modes while others exhibit a single primary peak. There is no single preferred trend apparent at all 36 sites and no trend that can be said to conform consistently with the former direction of regional ice movement.

Before comparing these results with those recorded by other workers, it is necessary to define in specific terms the landforms covered by this discussion. A review of the literature demonstrates that a great many landforms deposited by glaciers are both composed of till and orientated transverse to the direction of ice flow, and the literature is no less prodigious concerning workers who have carried out till fabric analysis on these features. Beneath this general umbrella are included investigations on end moraines of various kinds (e.g. King 1969; Price 1970; Mickelson and Birkson 1974; Mills 1975); cross valley or De Geer moraines (e.g. Andrews 1963a,b; Smithson 1965; Andrews and Smithson 1966; Barnett and Holdsworth 1972); hummocky moraine (e.g. Hoppe 1952; Gravenor and Kupsch 1959; Stalker 1960; Parizek 1969; Aartolahti 1974; Cullingford and Gregory 1978); "washboard moraines" (e.g. Mawdsley 1936; Gwynne 1951; Elson 1957; Løken and Leahy 1964; Nielson 1970);

and "ribbed" or Rogen moraines (e.g. Hughes 1964; Cowan 1968; J. Lundqvist 1969b).

However, the detailed evidence presented in Chapters 7 to 10 on the morphology, sedimentology and landform associations of the cross-valley ridges located in the Carsphairn area suggests that many of the landforms listed above may be eliminated from this discussion (see Chapter 12 for further discussion). The cross-valley ridges appear to resemble, quite closely, the larger types of transverse moraines as described by Prest (1968), but also possess certain affinities to hummocky moraine (J. Lundqvist 1978, pers. comm.). The former are known by a variety of names, although they are generally referred to as "ribbed moraine" in North America (Ives 1956; Lee 1959; Hughes 1964; Cowan 1968) and "Rogen moraine" in Scandinavia (G. Lundqvist 1937; J. Lundqvist 1969b, 1970; Aario 1977a,b). Thus this section will consider the till fabric patterns that have been published by workers who have investigated hummocky and Rogen moraines and these will be discussed with reference to those recorded from the cross-valley ridges in the Carsphairn area.

G. Lundqvist (1937), in one of the earliest studies on Rogen moraines, stated that the till fabrics in the ridges by Härjedalen

in central Sweden showed a preferred trend "transverse"* to the ridge crest. Hoppe (1952) in his study of hummocky moraine in Sweden presented nine fabrics (1952, Figure 36) sampled from ridges located in the Rogen area of Sweden (the type area for the development of Rogen moraines). The primary modes of these fabrics are aligned either obliquely or perpendicular to the moraine crests.

A study by J. Lundqvist (1958) of the Rogen moraines located in the Ösjö region of Sweden showed that the till fabrics there are rather more variable (1958, Figure 48), being orientated either "discordantly" or "parallel" with the trend of the ridge axis. Further work by J. Lundqvist (1969b) also suggests that the fabrics are orientated "transverse" to the ridges even in instances where the Rogen moraines are aligned oblique to the predominant ice flow direction. Lundqvist (1969b, p.21) concluded that "a common feature in all the examples mentioned here is that the orientation is evidently more dependent on the direction of the ridge than on the direction of ice movement". Kujansuu (1967) also recorded similar

* Within this section, reviewing the literature of till fabric analyses carried out on Rogen moraines, those adjectives in inverted commas denote undefined terms used by referenced authors for the relationship between fabric trends and Rogen moraine alignment. Where similar terms are used but are not enclosed in inverted commas, they represent the writer's interpretation of the fabric diagrams shown in the referenced papers, which are based on the definitions presented on p. 284 .

patterns from the Rogen moraines located in the Enontekiö region of NW Finland.

Till macro-fabrics recorded from ribbed moraine in Labrador, Canada by Ives (1956) showed no preferred trends, while those measured by Hughes (1964) from the Nichicun-Kaniapiskau area of Quebec paralleled the final direction of regional ice movement rather than any morphological trend in the ribbed moraine. Detailed till fabric analysis was also carried out by Cowan (1968) on the ribbed moraine of the Schefferville area, W-C Labrador. Although the results of Cowan's work must be treated with some caution owing to (a) his use of the invalid three-dimensional vector summation technique in the analysis of the fabrics, and (b) his having sampled fabrics at depths of "30 to 50 inches" (1968, p.1148), so that they may have been subject to frost heave, in general the fabrics measured from both proximal and distal slopes have a preferred trend that is either oblique or perpendicular to the alignment of the moraine crest. The absence of till fabric diagrams from Cowan's paper makes further interpretation of his results impossible.

Cross-valley till ridges orientated perpendicular to the direction of former ice movement have also been described by Tucker (1974) from W-C Newfoundland. The results of till fabric analysis showed primary modes both "parallel" with and "normal" to the ridge axes. Observations by Rogerson and Tucker (1972, p.27) on similar landforms located on the Avalon Peninsula, Newfoundland showed that the primary modes of fabrics were " . . . seldom perfectly normal to the crest orientation of the moraine".

The most recent work published from similar features in Scandinavia is by Aario *et al.* (1974), who described till fabrics from "moraine hummocks" that bear " . . . a resemblance to Rogen moraine" (1974, p.21 and Figure 14) in the Koillismaa area, NE Finland. Poorly developed trends with no distinct maxima were obtained; similar fabric patterns have also been recorded by Minell (1977a) from "hog's-back" moraines located in northern Sweden.

This brief review of the till fabric results recorded by other workers tends to demonstrate that in many cases the relationship between fabric trend and ridge orientation is not a simple one. Far from the classic interpretation of all fabric trends being "transverse" to ridge alignment, it would seem that a variety of relationships pertain. This also appears to accord with the till fabric results obtained from the cross-valley ridges in the Carsphairn area. Although the unimodal fabrics showed a relationship with direction of ice movement and ridge orientation (19 per cent of the total fabrics sampled), only 7 per cent of the fabrics that were considered to be bimodal or multimodal possessed major modes lying perpendicular to the ridge axes, while 10 per cent were oblique to the crests. Yet 50 per cent of all the fabrics showed equally developed primary modes that paralleled both ridge orientation and direction of former ice movement.

These observations suggest that a complex series of interacting processes was operating to produce the fabric patterns. Certain fabric patterns indicate that their development was controlled by ice movement, with modes paralleling directions of former ice flow as recorded by ice-moulded landforms and erratics trains. At the same time, other fabrics tend to show that mechanisms of ridge formation

were controlling the fabric pattern, with major modes paralleling ridge crests and a high percentage of individual pebbles lying parallel to ridge alignments. These mechanisms are partly governed by the condition of the till at the time of ridge formation; this relationship may provide clues to an understanding of the ridge-forming process and as such will be discussed further in Chapter 12.

Thus it should be emphasised that no specific conclusions concerning cross-valley ridge-forming mechanisms can be drawn from the analysis of till fabric data alone, despite other workers having done so (e.g. Hoppe 1952). The numerous and variable factors influencing both fabric development and their field measurement as detailed on pp. 244 and 263, suggest that care should be taken in their interpretation and that comparisons with results from other fieldwork techniques employed is essential. Nevertheless, it is possible to examine the till fabric results in terms of the environment of deposition of the till comprising the cross-valley-ridges in the Carsphairn area.

One hypothesis that might explain the till fabric patterns is that the cross-valley ridges were formed in a supraglacial environment. In this case, englacial debris bands are translated to a supraglacial position at the glacier margin during ice stagnation. The subsequent development of flow tills and the form of the underlying ice cores would determine the final ridge morphology (Boulton 1968, 1971; Kurimo 1977).

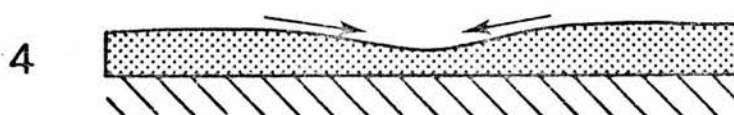
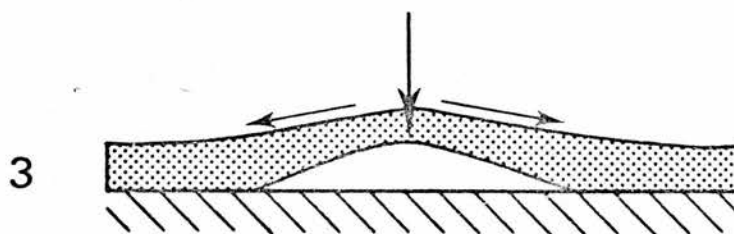
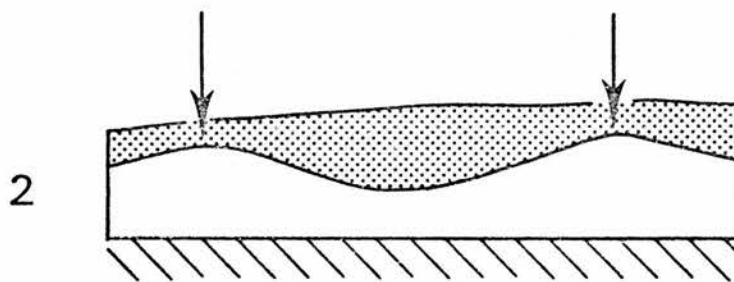
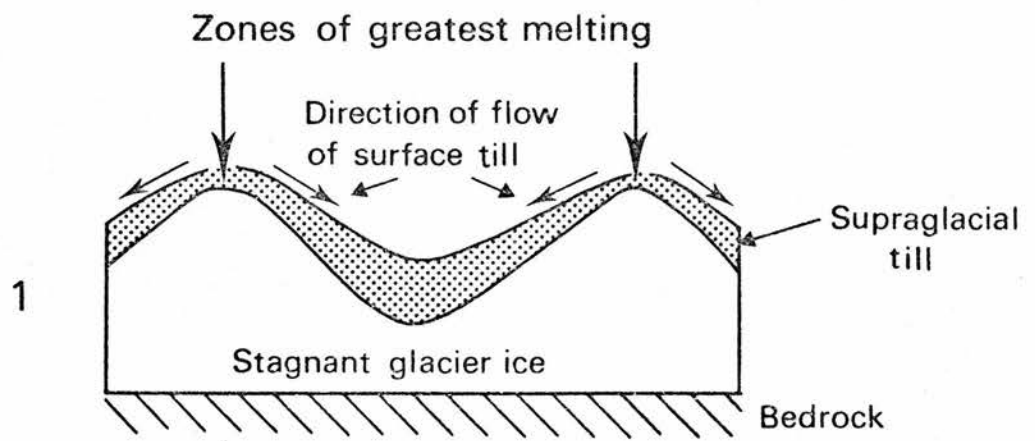
Boulton (1971) presented evidence from modern glaciers to demonstrate that flow tills showed considerable areal variations in fabric pattern and that these were related to the shape of the

underlying ice surface, which was in turn controlled by differential ablation rates. His results tended to show that whichever mode of flow (mobile flow, semi-plastic flow, downslope creep) developed in flow tills, fabric patterns within the body of the till exhibited preferred orientations parallel to the direction of flow. Variations did occur, however, especially at the "nose" of individual flow units where compression produced fabrics orientated transverse to flow (cf. Lundqvist 1949).

More specifically Boulton (1968, 1971) discussed the evolution of what he termed "'controlled' ice-cored moraines" (1968,p.397). These comprised a series of ice cores arranged parallel to the ice margin, which were covered uniformly by till derived from debris bands also striking parallel to the ice margin. Boulton suggested that in such a scheme, much of the flow in the supraglacial till would be either toward or away from the glacier (and therefore by inference perpendicular to the long axes of the ice cores) and that the resulting fabrics would tend to show peaks either parallel to or transverse to flow (or glacier movement).

In this way, it may be possible to explain the occurrence of unimodal fabrics within the cross-valley ridges, but it does not account for the limited number of fabrics where the preferred trend ($n = 6$) of the fabric or the preferred dip of individual pebbles ($n = 6$) is perpendicular to the ridge crests. More important, however, the evolution of "controlled" ice-cored moraines has been described from present glacier margins. Boulton (1971) did not produce any evidence to show what the resulting fabric patterns would be after complete melting of the ice cores. Figure 11.15 adapted from Boulton

Figure 11.15 The changing pattern of differential ablation
and flow producing flow till sheets of low
relief allowing buried ice to melt
(after Boulton 1971).



(1971, Figure 1) indicates that the flow of supraglacial till may be in opposite directions at varying times as the ice cores progressively melt. Thus it is difficult to envisage strong unimodal fabrics surviving under such variable conditions of flow (cf. Marcussen 1975).

An alternative hypothesis is that the cross-valley ridges were formed subglacially. If this were so, then the apparent anomalies described above concerning the supraglacial hypothesis might be explained. This would obviously be the case with the unimodal fabrics, whose preferred trends generally parallel the direction of former ice movement and thus imply that ice was still active at the time of fabric formation and therefore till deposition. The unimodal fabrics also show a relationship with ridge orientation and as such probably to the ridge-forming process. These two relationships suggest that both ice movement and ridge-forming mechanisms are interlinked and that the only reasonable explanation for this interaction would seem to lie in their being operative in a subglacial environment.

It should also be emphasised that direction of ice movement and the ridge-forming mechanism are not the only factors that influenced the observed fabric patterns. Ice velocity, particle-size composition of the till, morphology of the Carsphairn Lane - Water of Deugh valley, and the physical "condition" of the till beneath the ice must also be viewed as possibly having affected, directly or indirectly, the till fabric patterns.

11.3.5 Summary and conclusions

Till macro-fabric data collected from the cross-valley ridges in the Carsphairn area exhibit a variety of patterns ranging from strongly developed unimodal trends to multimodal forms. The unimodal fabrics show a relationship between mean trend and the direction of former ice movement in the area. They also display a relationship to the orientation of the cross-valley ridges, being aligned parallel or oblique to the mean trend of the crests. Bimodal and multimodal fabrics show a more diverse relationship with reference to ice movement and ridge orientation, but seem to reflect the general view, as expressed in the literature review, that not all fabrics sampled from this type of landform possess fabric trends that are perpendicular to ridge axis orientations. Analysis of individual pebbles showed a preferred orientation (in terms of frequency) parallel to the ridge axis, although this was found/ ^{not} to be statistically significant. In addition, no geographical correlation was found between the type of fabric, its relationship to ice movement or ridge orientation or the position within the ridges that the fabrics were measured.

Mean pebble dips showed similar values whether sampled from proximal, distal or the central parts of ridges, while those dipping perpendicular to and away from ridge crests showed no significant correlations with the mean slope angle of the ridge.

It is concluded that these results lend support to the arguments presented elsewhere that the cross-valley ridges were formed in a subglacial environment. In addition, it is suggested that a complex system of interacting processes, the most important being ice

movement and the ridge-forming mechanism itself, was operating at the time of deposition of the till and that this served to influence the development of the fabric patterns recorded.

CHAPTER TWELVE
DISCUSSION OF THE ORIGINS OF THE
CROSS-VALLEY RIDGES IN THE
CARSPHAIRN AREA

12.1 INTRODUCTION

This chapter attempts to provide a hypothesis for the origins of the cross-valley ridges of the Carsphairn area. The discussion will draw on evidence presented previously concerning the morphology of the features, particle-size, particle roundness, till macro-fabric and geotechnical properties of the till, and the distribution of glacial erratics trains. Aspects of current glaciological theory and observation will also be utilised.

The chapter is divided into three sections. First, the literature is reviewed in order to define the class of landform with which the cross-valley ridges are comparable (this extends the discussion in Chapter 11). Secondly, the major hypotheses that have been put forward for the origins of such landforms are discussed and assessed in the light of evidence from the Carsphairn area. Finally a hypothesis is presented for the origin of the cross-valley ridges in the Carsphairn area.

12.2 LITERATURE REVIEW OF CERTAIN "CROSS-VALLEY" LANDFORMS

As discussed in Chapter 11, various types of landform composed of till and trending perpendicular to ice movement appear very similar to one another, but it is certain that they have a number of different

origins (Prest 1968; Elson 1969). However, the specific landform associations, morphology and inferred subglacial origin for the till comprising the cross-valley ridges described in Chapters 7 to 11 can be used to identify the group of landforms with which they are associated. This evidence indicates that the Carsphairn cross-valley ridges closely resemble the "ribbed" or Rogen (both terms are used synonymously) moraines that have been described from Canada and Scandinavia respectively.

This review will therefore deal with the work published on these forms as well as those that, on the present writer's interpretation, possess affinities to "ribbed" or Rogen moraines but have not been referred to as such by the authors concerned. A table is provided that lists the major works published on "ribbed" and Rogen moraines and the characteristic properties of these forms (Table 12.1).

Rogen moraines were originally interpreted as end moraines by early Swedish workers (e.g. Frödin 1913, 1925; Högbom 1920) owing to their terminal moraine-like morphology and their orientation perpendicular to former ice movement. G. Lundqvist (1937) raised objections to this hypothesis, showing that the features occur in former ice-divide zones as well as in association with "dead-ice moraine". This evidence led Lundqvist to suggest a supraglacial origin for Rogen moraine, namely formation within crevasses on stagnant ice close to the glacier margin; later ice reactivation created the final morphology of the landforms and was responsible for the strongly developed transverse till fabric patterns from the ridges. Later, Mannerfelt (1945) suggested a compromising hypothesis that involved the accumulation of debris both subglacially and in open crevasses.

An entirely subglacial origin for Rogen moraines was advocated by Granlund (1943), who suggested that the ridges were formed by till being squeezed into basal crevasses by the weight of overlying ice. This hypothesis was developed by Hoppe (1952, 1957, 1959) to include hummocky moraine and Rogen moraine. Hoppe outlined three main reasons for accepting the subglacial squeezing hypothesis:

- 1) in some cases eskers and drumlins are superimposed on the Rogen moraines (or hummocky moraine) and "ice-margin meltwater channels may occur on higher parts of the ridge" (Hoppe 1959, p.205);
- 2) the tough and compact nature of the till comprising the ridges;
- 3) the preferred orientation of till fabrics perpendicular (in general) to the ridge crests.

Hare (1959) noted the relationship between drumlins and ribbed moraine in western Labrador (as have numerous other workers in Canada and Scandinavia; e.g. Hughes 1964; Elson 1968; Prest 1989; Lundqvist 1969a and b; Aario et al. 1974) and suggested a common origin for the two landforms by the over-riding of readvancing glaciers.

Both Ives (1956) and Cowan (1968) described the ribbed moraine located in the Schefferville area in west-central Labrador/Quebec. Tanner (1944) regarded these landforms as being typical of dead-ice topography, formed by debris being washed into crevasses in stagnant ice. Ives (1956) showed that the ribbed moraines are orientated perpendicular to former ice movement and that they merge down-ice into drumlinoid landforms. In addition Ives drew attention to the

relationship between the ridges and eskers in the area, suggesting that both were formed contemporaneously and subglacially, although he offered no actual mechanism for the formation of the ridges.

In a later study Cowan (1968) described the sedimentary properties of the tills in the same area and found the particle-size characteristics to be similar in the ridges, the inter-ridge areas and the superimposed drumlinoids and flutes. He suggested that the sub-horizontal fissile structure and hard, compact nature of the till indicated a subglacial origin for the debris. As he could find no stratigraphical relationship between the eskers and ridges, Cowan concluded that the former were deposited after the ridges had been formed. The formation of the ribbed moraine was associated with the reactivation of a retreating ice front, which led to the bulldozing and eventual over-riding of proglacial till deposits, although Cowan presented no evidence for this assertion. The adjacent drumlinoids and fluting were interpreted as being the result of a change of process near the ice margin where debris was remoulded by flow from subglacial high pressure areas to low pressure areas (cf. Gravenor and Meneley 1958). This hypothesis was an extension of that proposed by Lee (1959, 1962) for the origin of ribbed moraine in the southern Keewatin area, NWT. Lee suggested a subglacial origin near the ice margin, the ridges resulting from the over-riding by reactivated ice of basal ice heavily charged with debris.

Henderson (1958) also described ribbed moraine from the Dyke Lake area, western Labrador, and suggested that the features were composed of lodgement till (due to the compact nature of the till). He considered that the ridges were formed at a retreating ice margin,

each ridge possibly marking an annual position of the ice front. However, judging by Henderson's description of the size of the ridges (2 - 3 m) it seems more likely that these are more akin to the "washboard or minor moraine" type of landform.

Ribbed moraines were also investigated by Hughes (1964) in NW Quebec. He described individual ridges 10 - 30 m high, over 1 km long and with crests 100 to 300 m apart. Hughes suggested that there was an altitudinal relationship between the ribbed moraines and the drumlinised areas; the former occupying shallow depressions and the drumlins "low swells" (Hughes 1964, p.6). However, no origin for the ribbed moraines was offered by Hughes, although he suggested that the deposits in the area in general (including hummocky moraine) may have been derived from wasting ice. Since some of the ridges were grouped close to deltaic expansions of eskers he suggested that pro-glacial lakes may have been involved in their formation.

Kujansuu (1967) studied Rogen moraines in NW Finland and favoured Hoppe's (1952) interpretation for their formation. Till fabric patterns and eskers were used as arguments for a subglacial origin.

In review articles of moraine landforms both Elson (1969) and Prest (1968) outlined the characteristic features of ribbed/Rogen moraines, which although providing no mechanism of formation does afford insight into their possible environment of deposition. Elson stated that ribbed moraines are commonly found in the central parts of areas covered by former ice-sheets as well as in ice-divide zones. Prest (1968, p.6) noted that they may show a close association with longitudinal ice-flow features (and eskers) and

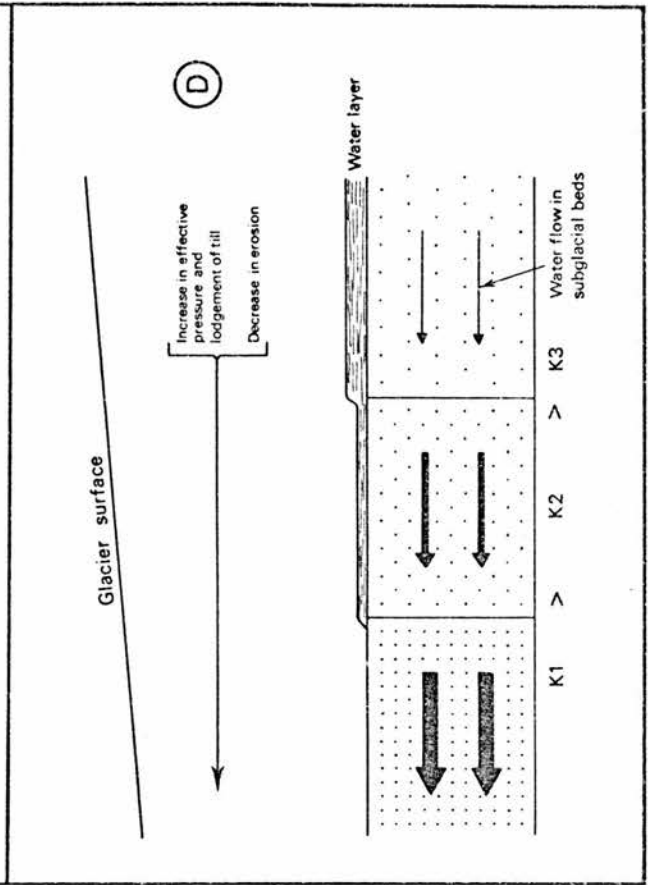
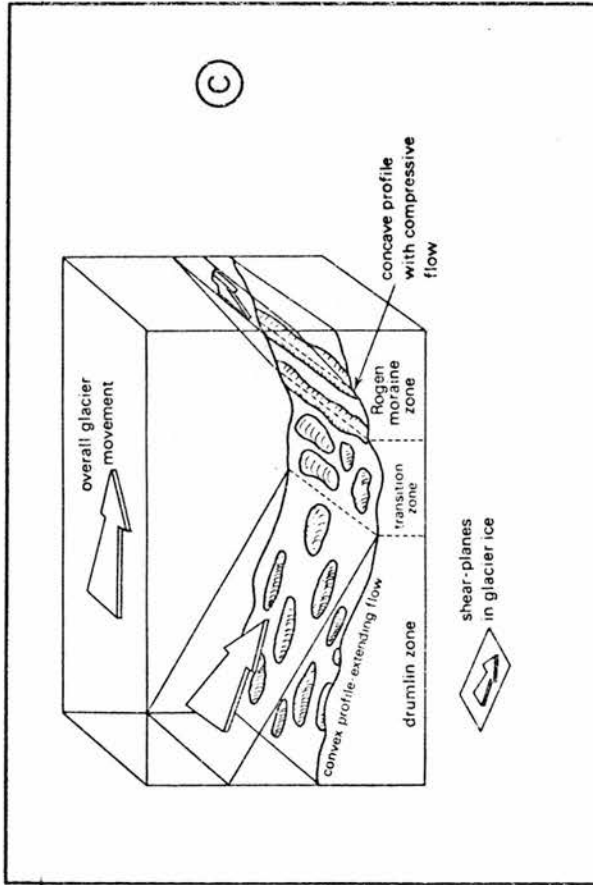
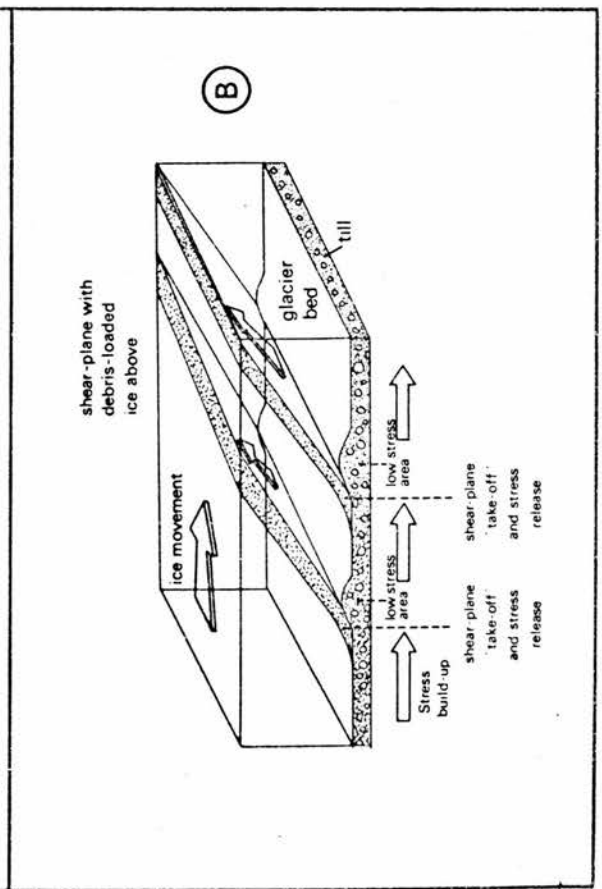
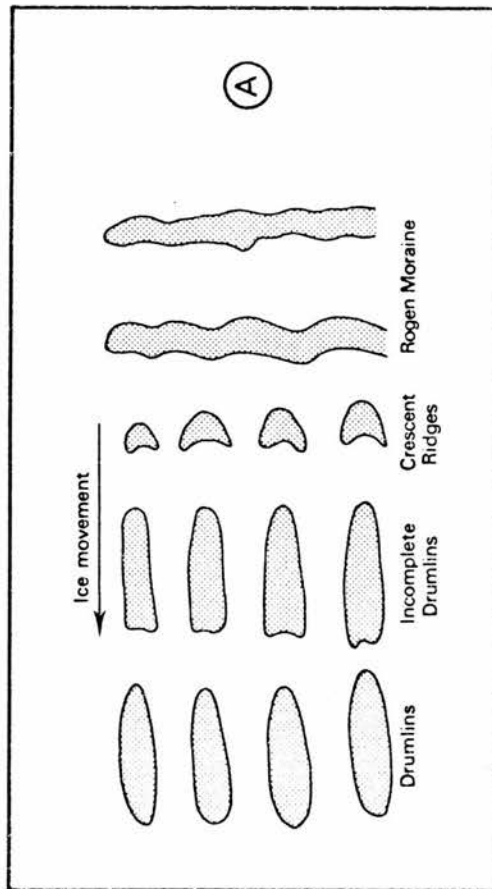
suggested that they " . . . may have a fluted or drumlinised surface that appears to be intimately related to the ribbing process rather than to a later, over-riding process".

The most extensive work published on Rogen moraines is that by J. Lundqvist (1969b), who produced a detailed synthesis. This paper therefore warrants careful consideration. According to Lundqvist, the following appear to be the most important characteristics of Rogen moraines.

- 1) The Rogen moraines of Sweden are largely associated with former ice-divide zones. (A similar location was also described by Lee (1959) and Drummond (1965) for ribbed moraines in Canada.)
- 2) They are located in valley or basin areas. In the former the ridges are normally orientated perpendicular to the valley axes, but in places they may trend obliquely to the valley axes or even along them. Whatever the orientation of the ridges, however, the valleys are invariably parallel with the direction of former ice movement. Within the basins the ridges generally occur in areas that have a concave topographic profile down-ice. Where the topography tends to convexity the ridges tend to become more drumlinoid in shape. The ridges may extend completely across a basin or may extend only a short distance from the valley sides towards the centre of the depression.
- 3) The ridges are usually 10 - 20 m high, but can exceed 30 m. They are normally ca. 100 m wide and the spacing between them is about the same order as their width.

Figure 12.1

- A. Diagram showing the transition of Rogen moraines into drumlins (after Lundqvist 1970);
- B. Diagram illustrating the hypothesis of Rogen moraine formation after Sugden and John (1976);
- C. Diagram illustrating the hypothetical relationship between drumlins and Rogen moraines (after Sugden and John 1976);
- D. Diagram showing the effect of the permeability (K) of subglacial beds on the thickness of a basal water layer (after Boulton 1972b).



- 4) The cross-profiles of the ridges are characteristically asymmetrical (the distal slope generally being the steeper); in plan they are usually branching or anastomosing and crest height is invariably constant. The upper surfaces of the ridges may show signs of drumlinisation.
- 5) The till comprising the Rogen moraines is very variable, but the most common material seems to be compact lodgement till. In the inter-ridge areas the till is usually quite thin.
- 6) The Rogen moraines show morphological transitions into drumlin landscapes. Figure 12.1A shows this transition, with the drumlins becoming shorter and converted into crescent-shaped mounds that extend in a direction perpendicular to drumlin orientation. These mounds in places combine to form long ridges that lie at right angles to the former direction of ice flow: these are the Rogen moraines. The Rogen moraines tend to merge into drumlins laterally rather than down-ice from the ice-shed zones.
- 7) The Rogen moraines seem to be commonly associated with eskers, which are either perpendicular or parallel to the ridge trends.

From these characteristics Lundqvist (1969b) proposed that Rogen moraines were formed subglacially beneath active ice in zones of tension, where basal transverse crevassing (caused by the concave topographic profile) promoted the deposition of till from debris-laden ice into ridges, each ridge coinciding with the position of a major transverse crevasse. Lundqvist (1969b, p.30) concluded that the "fragile structure (of the Rogen moraines) probably requires dead-ice wastage to be preserved. If the margin of an active ice-sheet

recedes across a tract where Rogen moraine was earlier initiated, the ridge structure will probably be more or less destroyed".

Rogerson and Tucker (1972) described what they considered to be ribbed moraine from the Avalon Peninsula, Newfoundland. The till ridges were 10 - 30 m high, perpendicular to the former direction of ice flow and passed laterally into drumlins. The authors suggested that the ridges were deposited during "a period of active dispersal preceding the ultimate recession of Avalon ice" (1972, p.27), but they offered no hypothesis for their formation. Henderson (1972) considered the same landforms and interpreted them as recessional moraines deposited from the pushing-up of marginal debris into ridges by small advances of the retreating ice-sheet. In support of this interpretation he drew attention to their arcuate morphology, their alignment transverse to the direction of former ice movement, their steep proximal slopes and the lack of dead-ice deposits in the area.

Tucker (1974) working in west-central Newfoundland described a series of till ridges that he equated with ribbed moraines. These ridges were regarded as being drumlins that had been reworked by later ice movements to produce "recessional-ablation moraine" (1974, p.11). The landforms in the same area had previously been discussed by J. Lundqvist (1965) who noted the relationship between these ridges and the drumlins and the location of both on valley floors. Lundqvist suggested that although the ridges were transverse to former ice movement, they were formed by an ablation process where ice stagnated in valleys that were orientated parallel with former ice movement.

Sugden and John (1976), following Prest (1968), suggested that Rogen moraines and their drumlinised surfaces had a common origin

and that this reflected some form of interaction between debris load, basal ice temperatures and type of ice movement. They indicated that Rogen moraines may form where irregularly spaced transverse stress fields occur on the glacier bed (possibly created by conditions of compressive ice flow in topographic concavities) and that this would produce an upward shearing of ice layers along thrust planes (Figure 12.1 B and C), which might accentuate pressure melting, lodgement of till and therefore ridge construction. Ridge length was considered to have been controlled by the longitudinal extension of the shear plane across the glacier bed. Sugden and John envisaged that, once established, the presence of the ridge would encourage the continued shearing of ice over its crest, which would help its preservation and allow further growth by lodgement of till. Sugden and John also suggested that Rogen moraines may be related to moraines formed by the subglacial shearing of large bedrock slices which have subsequently been mantled by till (cf. Kupsch 1962; Moran 1971; Minell 1977b; Sauer 1978).

A similar hypothesis was presented by Shilts (1977), who described ribbed moraine from the Keewatin area of the Canadian Shield. He considered that the ridges were formed during periods of active ice flow, as they were seen either to pass laterally into drumlinised plains or the ridges were themselves partly drumlinised. Shilts (1977, pp.206 and 207) suggested that the ribbed moraines were formed either as the "upturned edges of shear plates of till, stacked one on the back of the other, or the relicts of boulder-charged shear planes in the glacier". Although the present writer can see no real difference between these two proposed modes of origin, Shilts does make several

interesting points, stating that the ridges must have been deposited from ice abnormally charged with debris and that they tend to occur down-ice from rocks or topographic features that were particularly easily eroded owing to either soft lithology, structural weaknesses or heavy development of felsenmeer.

In a study of the Koillismaa and Kuusamo areas of north and NE Finland, Aario (1977a,b) and Aario et al. (1974) described the areal association of Rogen moraines, drumlins and flutes (the "hummocky active-ice assemblage"). They made an altitudinal differentiation between Rogen moraines and drumlins on higher ground and stagnant ice deposits (the "hummocky disintegration moraine assemblage") on lower ground. Aario, presenting little field evidence, suggested that various subglacial ice-flow phenomena were the primary cause of the Rogen moraine - drumlin landform assemblage. He proposed that the drumlins were formed by a combination of longitudinal and spiral ice flow, while the Rogen moraines were formed by an undulating (wave motion) ice flow. It was suggested that the "flow environment was governed by different local factors, those usually related to concave topography" (Aario 1977b, p.67). However, Kurimo (1977) considering the western part of the area investigated by Aario et al. (1974) described the material of the Rogen moraines mentioned above as consisting of deformed layers of unsorted till alternating with lenses of sorted outwash deposits. Collapse structures were also observed within these deposits and, according to Kurimo, lodgement till was absent from the landforms in the area. The Rogen-like ridges were therefore interpreted as controlled ice-disintegration features built up of material derived from englacial debris bands

orientated parallel to the margin of the ice-sheet (cf. Boulton 1968, 1972a).

In a brief study Minell (1977a) described a series of till ridges from northern Sweden orientated perpendicular to the direction of former ice movement. The till comprising the ridges was shown to be very friable in composition, from well-washed, sand-rich debris to silt- and clay-rich material. Eskers were also observed in the area and the ridges were seen to merge into hummocky moraine towards the north. Minell interpreted the ridges as having been formed supraglacially, the debris having been brought to the ice surface along shear planes.

Finally, Carl (1977, 1978) proposed that the till ridges, with associated drumlins and fluting (originally described by MacClintok and Stewart (1965)), located in the St Lawrence Valley, NW New York, USA, were akin to Rogen and ribbed moraine. He regarded the ridges as "till megaripples" that were formed in response to glacier over-riding. The gradation of the till ridges into drumlins was explained as being controlled by secondary, helicoidal flow in the ice or till (cf. Shaw 1975). Carl (1978, p.566) maintained that the till ridges were "a metastable member of a family of subglacial bedforms that may form simultaneously or in sequence".

12.3 MAJOR HYPOTHESES CONSIDERED FOR THE FORMATION OF ROGEN/RIBBED MORaine

From this literature review two levels of discussion emerge. First, there seems to be a conflict over the exact environment within which the Rogen or ribbed moraines were deposited. In broad terms

these arguments fall into three categories:

- 1) frontal or ice-marginal deposition;
- 2) supraglacial deposition;
- 3) subglacial deposition.

Although certain writers have argued for complex compromises between any two of the above categories (e.g. Mannerfelt 1945), it is clear that most workers firmly argue for ridge formation in one of the above three environments.

Secondly, there is a wide ranging discussion concerning the actual mechanism of formation of the Rogen or ribbed moraines, although not all workers have attempted to provide a hypothesis for their formation.

These two aspects are discussed below.

(a) Environment of deposition

1) Frontal or ice-marginal formation

This environment of deposition was proposed for the cross-valley ridges in the Carsphairn area by Charlesworth (1926a), who stated that they were recessional moraines. This interpretation is rejected for four reasons.

- (i) The ridges are not arcuate in plan as would be expected if they were formed at a lobate ice margin.
- (ii) Most of the ridges terminate at the valley axis (Figure 7.7).
- (iii) The ice-divide location of the Carsphairn cross-valley ridges is against marginal formation, for it is difficult to envisage the ice retreating all the way to its source leaving a series of recessional moraines in its wake.

- (iv) The close spatial association between drumlins and cross-valley ridges, as well as the drumlinisation of certain ridges, cannot be explained by the ice-margin hypothesis.

2) Supraglacial formation

The formation of Rogen or ribbed moraines in a supraglacial environment, either through the emplacement of material onto the ice surface via shear planes or debris bands or the accumulation of debris in crevasses developed within stagnant ice, has been advocated by G. Lundqvist (1937), Tanner (1944), Hughes (1964), Kurimo (1977) and Minell (1977a). Synthesising the evidence presented in Chapters 7 to 11, five lines of evidence are against the formation of the Carsphairn cross-valley ridges in a supraglacial environment.

- (i) Interbedded, stratified sand and gravel deposits, which are characteristic of supraglacial debris accumulations (Boulton 1967, 1968), are absent from the till comprising the cross-valley ridges.
- (ii) The high percentages (>30 per cent) of silt-size material in the olive till suggests that it has not been subject to the washing processes that operate in a supraglacial environment (cf. Cullingford and Gregory 1978).
- (iii) The close affinity between the particle-size distribution of the olive till comprising both the cross-valley ridges in the Carsphairn area and the drumlinoid landforms into which the former merge, suggests a genetic relationship, and, as drumlins are known to be formed subglacially, then

the cross-valley ridges may also have been formed in a similar environment.

- (iv) The close landform association between the cross-valley ridges and drumlinoids/drumlins (as has been found by numerous other workers (Table 12.1)) argues against a supraglacial formation.
- (v) The olive and grey tills are both compact and indurated and show some form of fissile structure throughout the area occupied by the cross-valley ridges. Certain workers have used this property to establish the position of deposition of tills comprising Rogen/ribbed moraine (e.g. Hoppe 1952; Cowan 1968), arguing that loosely compacted till is indicative of supraglacial (or ablation) deposition and indurated till of deposition by subglacial lodgement processes. On the other hand, Boulton (1975b) and Boulton and Paul (1976) have suggested that supraglacial till may become over consolidated if its water content is rapidly reduced by draining or evaporation, and therefore till hardness should not be considered as a diagnostic feature of lodgement till. However, supraglacial desiccation of the till usually operates on only a small-scale where local factors are favourable. Thus it is suggested that the widespread and consistently compact nature of both the tills in the area can be used to support the arguments for rejecting the supraglacial hypothesis.

3) Subglacial formation

Since supraglacial and ice-marginal formation of the cross-valley ridges have been rejected a subglacial origin remains.

Further reasons for accepting a subglacial origin are as follows.

- (i) The landform continuum from valley-fill deposits through cross-valley ridges to drumlinoids and then drumlins suggests a subglacial origin.
- (ii) No other hypothesis explains the drumlinised surfaces of certain of the cross-valley ridges nor their drumlinoid form by Carminnow Farm (23, Figure 7.7).
- (iii) Eskers are closely associated with the cross-valley ridges in places (as in other areas (Table 12.1)). Since eskers are usually considered to have been formed subglacially, a similar origin is implied for the ridges.
- (iv) The compact nature of the olive till and the absence from the same till of sedimentary or collapse structures suggests a subglacial origin.
- (v) The coating of gravel-size clasts with thin layers of silt and the surrounding of many cobble- and gravel-size clasts by a lattice of openwork coarse sand-size particles are a ubiquitous characteristic of the olive till. These phenomena have been shown by Elson (1961) and Dreimanis (1976) to be indicators of basal melt-out tills.

(b) Mechanisms of formation

Various modes of subglacial origin for the ribbed/Rogen moraines have been proposed, each of which requires consideration. Three broad categories can be identified:

- 1) the subglacial squeezing hypothesis;
- 2) the subglacial shearing hypothesis;
- 3) the undulating ice flow hypothesis.

1) The subglacial squeezing hypothesis

The formation of ribbed/Rogen moraine by the squeezing of water-saturated till into basal crevasses in the ice has been proposed by Granlund (1943), Hoppe (1952, 1959) and Kujansuu (1967). This hypothesis has also been favoured for the formation of various types of hummocky moraine (e.g. Hoppe 1952, 1957; Gravenor and Kupsch 1959; Stalker 1960, 1973; Parizek 1969; Aartolahti 1974; Cullingford and Gregory 1978) as well as for other types of moraine ridge (e.g. Dyson 1952; Andrews 1963a,b; Andrews and Smithson 1966; Jewtuchowicz 1968; Price 1970; Mickelson and Berkson 1974; Paul and Evans 1974; Boulton 1976b) and for drumlins (e.g. Evenson 1971; Gillberg 1976).

There are several factors, however, that indicate that this mechanism was not responsible for formation of the cross-valley ridges in the Carsphairn area.

- (1) Part of Hoppe's (1952) hypothesis invoking a subglacial squeezing mechanism is based on his till fabric patterns showing a consistent preferred trend perpendicular to the ridge crest. However, analysis of the relationship

between the primary mode of till fabrics and the trend of cross-valley ridge crests (Chapter 11) showed that of the 36 fabrics sampled only six showed modes perpendicular to the ridge crests. The remainder were either oblique (5 fabrics), parallel (6 fabrics) or showed no clear relationship (19 fabrics). Similar patterns were also observed in analysis of the relationship between the preferred dip of individual pebbles and ridge crest alignment. The absence of any preferred fabric trend perpendicular to ridge orientation in the Carsphairn area therefore casts serious doubts on the formation of the ridges by the subglacial squeezing mechanism.

- (ii) The results of the Atterberg limit tests on the olive till (Chapter 9) show that it does not possess plastic limit or liquid limit properties. This indicates that the olive till does not readily flow in the presence of water, which implies that large-scale squeezing of the olive till into ridges up to 20 m high would be unlikely. That deformation structures in the olive till were observed only in the NW part of the Carsphairn Lane valley, where an englacial water-table existed (Chapter 7), tends to support this argument.
- (iii) The subglacial squeezing mechanism does not explain the morphological transition of cross-valley ridges into drumlinoid landforms down-ice. It may be argued that the ice-press mechanism formed the ridges and was then followed by drumlinisation (cf. Hoppe 1959). However,

if as suggested by Hoppe, ridge formation occurred while the ice was stagnant, a late-stage reactivation of ice would be required to create the drumlins. Such a reactivation is difficult to envisage in the Carsphairn area owing to the ice-shed location of the cross-valley ridges.

The mechanism of Rogen moraine formation proposed by J. Lundqvist (1969a,b, 1970, 1977) is related to the subglacial squeezing hypothesis in that he invoked the presence of transverse basal "fracture lines" and "open hollows" beneath ice-sheets. Lundqvist (1969b) described the possible formation of basal "fractures" in active ice as being due to tension caused by a combination of three factors:

- (i) the concave form of the topography beneath the ice;
- (ii) the lower "mobility" of the till-laden basal ice than "clearer" upper ice;
- (iii) the basal ice had to move a slightly longer distance than the surface ice.

According to Lundqvist (1969b, p.28) "The most plausible effect of the tension would be a division of less mobile, as a whole less plastic, till-loaded basal ice along fracture lines transverse to the movement. The gaps arising between the till-loaded parts would immediately be filled with till-free ice moving in from above". Thus the Rogen moraines form " . . . parts of the divided regional cover of basal till", with the inter-ridge areas corresponding to former zones of debris-free ice.

Although Lundqvist's ideas provide clues as to the condition of the ice/debris interface during till deposition as well as the

importance of local topography (referred to later), the hypothesis fails to answer three questions.

- (i) How was till precipitated from the debris-rich basal ice into a ridge form?
- (ii) How ^{did} the ridges, once formed, survive over-riding by the still active ice? This is necessary if, as Lundqvist implies, the adjacent drumlins were formed contemporaneously with the Rogen moraines.
- (iii) How ^{were} the basal "fracture lines" maintained within the ice? Indeed, it is yet to be established that basal crevassing actually occurs beneath the centre of ice-sheets. Although tension fractures are common at the surface of glaciers, formed when ice cannot deform rapidly enough to counteract stresses within it, at depth, however, plastic deformation within the ice would be far more effective and would tend to prevent fracturing (Haefeli 1970). Further, Röthlisberger (1972) and Weertman (1972) have shown that conduits associated with subglacial water flow will tend to close by mechanical deformation if ice pressure is greater than that offered by the water pressure, while Nye (1973) has suggested that subglacial tunnel closure may also occur by the "pinching out" of conduits by the forward motion of ice against bedrock obstacles. Examples of a squeezing mechanism producing ridges parallel to the ice front have all been investigated at the marginal zones of glaciers (e.g. Andrews and Smithson 1966; Price 1970;

Mickelson 1971, Mickelson and Berkson 1974). At these locations basal cavities and crevasses occur in the lee of boulders or bedrock knolls or where the glacier is actively calving and water-soaked till may be squeezed into these areas. However, Boulton (1974, p.80) has stated that because of increased ice thicknesses and low ice velocities beneath ice-sheets "cavitation will be suppressed only a little distance from the margin".

2) The subglacial shearing hypothesis

This hypothesis was suggested for the formation of Rogen moraines by Sugden and John (1976) and seems to be an extension of the observations made by Boulton (1970b) on Nordenskiöldbreen glacier in Spitzbergen. The concept of shearing and thrusting of englacial debris from basal layers in the ice to higher levels has been demonstrated by field observation (Boulton 1970a). It has also been shown that the shearing is associated with longitudinal compression and relatively high stresses within the ice and that the accompanying debris bands may be orientated transverse to the direction of ice flow (Boulton 1970a, 1972a). However, there are several objections to applying these observations to the formation of Rogen moraines.

- (i) The relatively high density of the Carsphairn cross-valley ridges (between 50 and 200 m apart) in a down-ice direction requires that many shear planes would have had to leave the glacier bed over a short horizontal distance in order to create the ridges; such a process seems difficult to envisage.
- (ii) The hypothesis fails to explain the actual mechanism that

would deposit till in the form of a ridge at the base of each shear plane. The shearing and thrusting process invoked by Sugden and John does not incorporate subglacial material into the ice, but merely moves debris already in an englacial position to higher levels (the debris already having been incorporated into the basal layers of the ice by "freezing-on" processes, see Weertman (1961), Boulton (1970a)). There seems to be no evidence from the studies of modern glaciers to indicate that till deposition will occur where shear planes leave the glacier bed. In addition, according to Sugden and John (1976, p.245) the upward movement of shear planes may "accentuate pressure melting, lodgement and hence gradual ridge construction". Thus by inference they consider that pressure melting is the major factor of till deposition in Rogen moraine formation. However, for till to be deposited in this way a form of obstruction is required against which the till may lodge. Once the till has started to accumulate then it is the interparticle friction between the till that is already lodged and the debris in traction that is primarily responsible for further lodgement (Boulton 1975a; Boulton and Paul 1976). Thus it is clear that the actual mechanics of subglacial shearing in Rogen moraine formation have been misapplied by Sugden and John.

- (iii) If the cross-valley ridges could be formed by this mechanism, it is difficult to see how they could maintain

their transverse form against removal or re-shaping by over-riding ice unless the physical properties of the till prevented ridge destruction: this important aspect was overlooked by Sugden and John.

- (iv) The hypothesis fails to explain the drumlinised surfaces or the drumlinoid form of certain of the cross-valley ridges in the Carsphairn area. Figure 12.1 C, taken from Sugden and John (1976, Figure 13.12), shows drumlins occurring in areas of extending ice flow and Rogen moraines in areas of compressive flow. However, by Carsphairn the two landforms are developed side by side or are superimposed. Moreover, where ice compression would be most expected to develop (by Dundough Hill), the cross-valley ridges become less linear, more massive and drumlinoidal in morphology.

3) The undulating ice flow hypothesis

Aario (1977a,b), using analogies with landforms created through the action of running water, considered that Rogen moraines were formed largely by the undulatory (wave) flow of active ice and that the ridges represent the forms of most resistance to this kind of flow. Although the hypothesis attempts to unify glacial and fluvial bed-forms (cf. Shaw 1975, 1977; Folk 1976) there are several critical factors of cross-valley ridge formation that it does not explain as well as certain fundamental objections concerning its actual existence in terms of glacier dynamics.

- (i) The hypothesis is based on the fallacious assumption that the same bed-forms that are created by fluvial activity

will also be produced by ice flow. Thus although bed-forms orientated transverse to flow may be those of least resistance in river or foreshore environments, the rate of deformation in ice is normally several orders of magnitude less than that of water. As a result the landforms of least resistance produced by moving ice will not be the same as those produced by water.

- (iii) The hypothesis does not explain the presence of drumlinoid landforms occurring within the area occupied by the cross-valley ridges, for according to Aario (1977a) and Carl (1978), the two types of landform are produced by two different modes of ice flow (drumlins by helicoidal flow and Rogen/ribbed moraines by undulating flow).
- (iii) In presenting his hypothesis Aario (1977a,b) gave no evidence for the existence of undulating (or of helicoidal) ice flow nor did he suggest how the till that forms the ridges was deposited, as well as how the ridges maintained their position, once formed, at the base of the glacier.

12.4 A HYPOTHESIS FOR THE FORMATION OF THE CROSS-VALLEY RIDGES IN THE CARSPHAIRN AREA

The above discussion has shown that all the hypotheses published on the origins of Rogen/ribbed moraine fail to explain the observations made on them. This section attempts to provide a hypothesis for the formation of these features in the Carsphairn area using the evidence given in previous chapters. This hypothesis might also be

extended to Rogen/ribbed moraines located elsewhere.

Of necessity, any hypothesis concerned with the formation of landforms of this nature must in part be based on inference and on deduction (Muller 1974). However, with increased knowledge of the subglacial environment and the mechanics of till deposition such inferences may be less theoretical and more factually based.

The following need to be explained:

- 1) the large amounts of till located in the former ice-divide zone;
- 2) the valley-fill - cross-valley ridge - drumlin landform association;
- 3) the deposition of the till into ridges;
- 4) why the cross-valley ridges are orientated perpendicular to former ice flow;
- 5) how the ridges could have survived over-riding by ice once formed;
- 6) at what stage during the Late-Devensian ice-sheet phase the ridges were formed.

In the light of these points, this section comprised three main parts.

- (i) The provision of debris in the Carsphairn area is considered with particular reference to the former ice-divide in that area.
- (ii) The stage at which cross-valley ridge formation occurred during the Late-Devensian glaciation is considered.
- (iii) The mode of deposition of the till and its formation into cross-valley ridges is discussed.
- (1) The provision of debris.

It can be assumed that an ice-sheet frozen to its bed (i.e. with a polar régime) could not have produced the cross-valley ridges or

drumlins since ice movement would have been by internal deformation. Thus formation of these landforms beneath temperate-based ice is inferred.

The temperate nature of the ice-sheet base has implications for the origin and transport of the till in the Carsphairn area. Numerous writers have drawn attention to the fact that temperate-based glaciers carry very little basally derived, englacial debris (Okko 1955; Boulton 1970a, 1972b; Vivian and Bocquet 1973; Boulton *et al.* 1974; Vivian 1975). Observations by these writers seem to indicate that debris is carried 0.5 - 1 m above the glacier sole, where the debris concentration varies from zero to 50 - 60 per cent by volume (Boulton 1974). It has been suggested that the products of erosion may be incorporated into this zone in two ways.

- 1) Water derived from pressure melting on the up-glacier side of obstructions on the glacier bed may refreeze on the down-glacier side beneath debris embedded in the sole (Kamb and LaChapelle 1964). This regelation ice is commonly charged with large amounts of debris. However, regelation ice formed behind one obstruction is often destroyed by pressure melting in front of subsequent similar-size obstructions.
- 2) The interaction between particles embedded in the ice and between these particles and the glacier bed may cause incorporation of debris at low levels in the ice (Boulton 1972b), which can lead to a build-up of quite dense particle aggregates that move as a unified mass.

These observations suggest that the amount of englacial debris carried by temperate-based glaciers is small. This conflicts with

the occurrence of large quantities of till in the former ice-divide zone in the Carsphairn area, where, in addition, as basal ice velocities would be of a low order the capacity for ice to erode would be almost eliminated.

However, the above-mentioned observations on englacial debris in temperate-based glaciers have necessarily been restricted to shallower and more easily accessible parts of glaciers, for example at the margins or in natural subglacial cavities. The deeper parts of ice-sheets have not been reached for observations to be made on the debris carried in these zones. Recent work by Engelhardt *et al.* (1978) using cable-tool drilling and borehole photography in studying the base of the temperate Blue Glacier, Washington, USA, in its accumulation area has demonstrated that the basal zone of debris-laden ice (englacial debris) may be up to 16 m thick. This implies that debris may be carried at higher levels than 0.5 - 1 m above the glacier sole in temperate-based glaciers.

Moreover, it has been argued in Chapter 5 that the till in the Carsphairn area was emplaced during build-up of the Late-Devensian ice-sheet. The termination of the Craig of Knockgray microgranite erratics train only 2.8 km from its source (which lies virtually on the former ice-divide), its anomalous spread through an arc of some 90° and the limited transport of Caradocian conglomerates in the same area support this view. The later development of an ice-divide in the area along with the topographic constrictions of Dundough Hill and Craig of Knockgray hill served to restrict horizontal ice movement, and therefore debris evacuation from the area, during the time the ice-sheet existed. Further corroborating evidence is provided

by the roundness analysis of clasts and sand-size particles from the tills of the area (Chapter 10). The rho mean roundness value for the olive till (which comprises the cross-valley ridges) in the 1.25 to 2.0 ϕ and -4 to -8 ϕ size ranges is 1.36 and 1.33 respectively, both of these values fall within the "angular" classification of Powers (1953). The results for the grey till are 1.63 and 1.57 respectively, the values again lying in the "angular" class. These results indicate that the till debris has undergone little transport (and thus little abrasion or crushing) by ice, which is in accord with their early emplacement into the area and preservation below the ice-shed. The absence of any rapid increase in the roundness of particles in the olive till towards sub-angularity, a characteristic of many clast roundness - glacier transport studies (e.g. Krumbein 1941b; Drake 1972; Reheis 1975; Boulton 1978), down-ice from the ice-shed zone supports this view. The absence of striae from any of the 3000 clasts analysed from the olive till could also be explained in this way, for the clasts would have little time in which to be striated.

(ii) The stage at which cross-valley ridge formation occurred.

This question largely relates to whether the formation of the cross-valley ridges occurred at a late stage of ice-sheet wastage in a marginal zone where the ice was thin or whether it occurred earlier when the ice was much thicker. Although there is no direct evidence to indicate the stage at which formation took place, certain inferences can be made.

That the cross-valley ridges were not formed at a late stage of ice-sheet decay is indicated by meltwater channels 27 and 28

(Figure 7.10), which cut through the ridges, implying that the latter were in existence prior to meltwater activity. The cross-valley ridges have been shown to merge into drumlins down-ice (Chapter 7). Observations on present-day glaciers (e.g. Boulton 1970b, 1971; Goldthwait 1974) have shown that drumlins may be formed beneath relatively thin ice. In addition, other workers have demonstrated that drumlins were formed in the marginal zones of Younger Dryas (Loch Lomond Advance) glaciers (Virkkala 1961, 1963; Rose and Letzer 1977) and the Late-Devensian ice-sheet (Boulton et al. 1977). These features, however, are normally muted in their morphology and have a restricted distribution. Furthermore, it cannot be assumed that all drumlins were formed under relatively thin ice. It is difficult to envisage the Galloway drumlin field (the NW part of which includes the drumlins shown in Figure 7.11) having been formed under thin ice, for it forms part of one of the most extensive drumlin fields in Great Britain, linking with the Solway drumlin field to the west as well as the Eden Valley and Tyne Gap fields in northern England. Such a large areal extent and the general parallel trend of the respective drumlin swarms within it demand that they be formed as a unit, under conditions of regional ice flow. In such a situation ice hundreds of metres in thickness would be required. Similarly Embleton and King (1975, p.421) have argued that the drumlin field to the north and NE of the Lake District "must have been formed by actively moving ice and not in the sub-marginal zone in which some drumlins seem to occur". The regional pattern of ice movement reflected in the Tweed drumlin field further supports the view of large-scale drumlin formation under thick ice (Clapperton 1970; Sissons 1976).

A morphological relationship has been shown to exist between the cross-valley ridges in the Carsphairn area and the drumlinoid and drumlin landforms down-ice from them (Chapter 7). In addition the sedimentological properties of the till comprising the cross-valley ridges and drumlinoids are almost identical (Chapters 8 and 10). These associations not only imply that the landforms are genetically related but also that they were formed beneath thick ice.

(iii) Mode of till deposition and formation of the cross-valley ridges.

Since the cross-valley ridges are composed of till, which has been shown to be of subglacial origin, then any attempt at explaining their formation requires some consideration of the mechanics of lodgement till deposition. Nobles and Weertman (1971) have suggested that lodgement till will be deposited if: (1) there is englacial debris in the lower levels of the ice and (2) if the temperature gradient at the base of the ice is insufficient to drain the geothermal heat or the heat produced by the friction of sliding. In addition, Boulton (1972b, 1975a) has listed other important factors that favour subglacial lodgement of till. These include the following.

- 1) Glacier bed roughness: this increases frictional drag and therefore promotes lodgement in certain areas. Pressure melting may also occur on the up-ice side of protruding hummocks.
- 2) Low ice velocities: this also increases the frictional drag of particles and promotes lodgement.
- 3) Large ice thicknesses: this increases effective pressure

which again increases lodgement.

- 4) The frictional characteristics of the transported debris:
large clasts ($>3.0 \phi$ in diameter) and small particles ($< 7.0 \phi$) will tend to lodge more easily than intermediate particle sizes.
- 5) Where the glacier bed is composed of permeable sediments, subglacial water pressure is reduced and effective pressure increased thus promoting lodgement. If the substrate is impermeable, lodgement can be assisted by removal of water through subglacial channels.

Many of these factors are interdependent and in particular factors (1), (2) and (3) above may be considerably influenced by the presence of subglacial water. This subglacial water may lubricate the glacier sole and reduce the effective normal pressure exerted by the overlying ice as well as the frictional drag component. Thus the deposition of the till is affected as well as any shearing or deformation of the lodged till. The existence, size and form of the subglacial water is dependent on the permeability of the subglacial beds and as such the effective pressure will be reduced where a glacier passes over impermeable beds and increased where it passes over permeable beds (Figure 12.1 D).

It is generally agreed that the mechanism by which till is deposited comprises the gradual release of debris from the ice in response to basal melting, and that under temperate ice-sheets this is largely in the form of pressure melting (Nobles and Weertman 1971; Embleton and King 1975). Individual particles are deposited where "the frictional drag between clasts in traction and the bed over which they move is such that the force imposed on them by the ice is

insufficient to maintain them in motion" (Boulton 1975a, p.20).

Lodgement may also be enhanced by frequent interparticle collisions. Once the till has started to accumulate then individual clasts that have become lodged provide obstructions against which other particles may become lodged. Boulton and Paul (1976) have suggested that clasts of boulder-size provide the most effective obstructions and thus deposition nuclei around which smaller particles and other boulders may readily lodge. They further suggest that these clusters of boulders make the till less compressible and increase its shear strength owing to the numerous inter-boulder contacts.

Such conditions of till deposition in the Carsphairn area during the Late-Devensian glaciation, along with thick ice of low velocity and the debris-rich basal ice layers argued for above, constrain the mechanism required to create and preserve the cross-valley ridges. A progressive change in the nature of till deposition is indicated in the Carsphairn area by the observed landform continuum, from an amorphous valley-fill spread to cross-valley ridge forms and then drumlins. Clearly such a morphological relationship would also be influenced by the response of the till at the base of the ice-sheet to the stresses imposed on it by the overlying ice. Thus if it is considered that the till acted in a dilatant manner then the formation and preservation of the cross-valley ridges might be explained.

A dilatancy hypothesis has already been proposed for the formation of drumlins by Smalley and Unwin (1968), which seems to answer some of the questions and enigmas provided by this landform. Dilatancy is a property common to all granular aggregates, regardless

of angularity of grains or degree of assortment (Reynolds 1885; Mead 1925); this definition therefore includes till. The phenomenon occurs in a material when the applied stress causes the mass to expand due to the movement of particles in relation to one another. This is manifested by an increase in the volume of the material due to an increase in the void spaces. From these facts, it is clear that the environment in which the material is located is all important for the development of dilatancy, since conditions must be such that expansion can take place (Reynolds 1885; Boswell 1961; Radhakrishna and Klym 1974).

Smalley and Unwin (1968) stated that there were two basic prerequisites for drumlin formation. First, the material at the base of the ice must have been continuously deforming and secondly, that the material must comprise boulders in a clay-water system, within which a range of stress levels operated. They suggested that if, within the deforming horizon, an obstruction interrupted the flow then the debris would locally pack into and around this obstruction, while elsewhere the deforming materials would continue to flow round the obstruction thereby shaping it into a drumlin form. Smalley and Unwin also outlined three stress zones within an ice-shed that, they suggested, accorded with varying ice thicknesses from its centre to its margin. These stress levels are:

Zone A: high stress levels; thick ice; constant deformation; near to the ice-sheet centre.

Zone B: low stress levels; thin ice; no deformation; near to the margin of the ice-sheet.

Zone C: intermediate stress levels; relatively thick ice; stress levels sufficient to maintain deformation but insufficient to initiate deformation if the debris became rigid; occurs between the marginal zone and ice-sheet centre; drumlins formed in this zone.

There are, however, several aspects of this hypothesis that require discussion, for in the light of more recent work, some of the above postulates have been found to be suspect, although they do not alter the credibility of the dilatancy phenomenon.

- 1) When a water-saturated material becomes dilatant, the pore-water pressures within it become negative causing a reduction in the shear strength of the material and a continuation of the deformation process (Mathews and MacKay 1960; Terzaghi and Peck 1967; Clayton and Moran 1974). Thus in order that the debris can agglomerate into a stable form on the glacier bed (i.e. increase its shear strength by achieving maximum density packing) it must first undergo changes in its rheological properties (Muller 1974). This point was not considered by Smalley and Unwin (1968).
- 2) Smalley and Unwin did not take into account the influence of subglacial water pressures on the effective pressure. As described above, the presence of water at the base of the ice-sheet would tend to reduce effective pressure, which is partly controlled by ice thickness. Therefore the stress zones described by Smalley and Unwin may not be as clearly defined as they suggest. The stress value is also influenced by bed roughness and the permeability of the subglacial bed, which

again serves to show that the concept of distinct stress zones in the ice is tenuous (Boulton *et al.* 1977).

- 3) Certain workers have shown that drumlins may form under thin ice (e.g. Virkkala 1961; Boulton 1971; Goldthwait 1974; Rose and Letzer 1977) which suggests that Smalley and Unwin's assertion that drumlins do not occur in the marginal, low stress zone "B" does not hold in all cases.

These points, however, can be accommodated in the dilatancy hypothesis and are discussed below. The actual property itself remains unaffected, for observations by Boulton *et al.* (1974) have shown that dilatancy does operate beneath present-day, temperate-based glaciers. They described how, at the margin of Breidamerkurjökull in SE Iceland, large boulders protruding through the glacier sole collided with other large clasts lodged in the basal till, or ploughed through the till matrix to produce dilation of the till. The phenomenon was produced by the movement of ice over the till which imposed shear stresses on it. If the shear strength of the till at some point was less than the shearing stress at that point then dilation occurred. Boulton *et al.* (1974) suggested that the thickness of the dilatant layer depended on:

- 1) the effective normal pressure;
- 2) the shear stress across the till/ice interface;
- 3) the frictional and cohesive properties of the till.

The average shear stress at the base of a glacier is between 0.5 and 1.6 bars (Nye 1952) and is independent of pressure. If the effective pressure (ice pressure less subglacial water pressure) is reduced as in the marginal zones of glaciers then, according to Boulton *et al.* (1974), shearing and dilatancy will occur in the till. Under greater

thicknesses of ice the shearing stresses will be smaller and the strength of the till will increase due to higher effective normal pressure; dilatancy will therefore be inhibited. But if subglacial water is present in this zone, effective pressure will again be reduced and dilatancy promoted (Boulton *et al.* 1974). The effectiveness of this latter process will depend to a large extent on the permeability of the subglacial beds. If this is low, then considerable areas of till may deform, because beds of low permeability act as dams to water flow thereby increasing water pressure in up-glacier areas (Boulton 1975a).

These observations suggest that dilation of till may occur over wide areas at the base of the ice, and it is possible that this may have occurred in the Carsphairn area. The intrinsic permeability of the greywacke bedrock in the area is very low, ranging from 2×10^{-4} to $2 \times 10^{-7} \text{ cm}^3 \text{ sec}^{-1}$ (Johnson 1974), which would have been conducive to the setting-up of high water pressures beneath the ice.

Thus far the sequence of events envisaged is as follows. Stagnant basal debris-rich ice accumulated in the Carsphairn Lane - Water of Deugh section of the main through valley owing to the meeting of valley glaciers, with opposing directions of flow, in that area during build up of the Late-Devensian ice-sheet. The later development of an ice-shed in the same area and the confining influence of local topography both served to restrict evacuation of debris from the area. During the lodgement phase, while ice thickness was still considerable, increased water pressure created by the impermeable nature of the bedrock reduced the effective pressures exerted by the overlying ice on the debris beneath. This in combination with the

stresses exerted on the debris by the slowly moving clean ice above allowed the till to deform (cf. Nye 1959). Excess porewater and subglacial water (produced by frictional melting and geothermal heat flux) was removed from the area via subglacial channels, thus enabling parts of the till to increase in shear strength and agglomerate into "proto-ridges".

There is, however, a paradox in this postulated series of events. As described above, for deformation of the till to occur under thick ice, there must be room for expansion. This may have been provided by increased water pressures (created by the low permeability of the bedrock materials), which would have served to reduce effective pressures exerted by the overlying ice. Yet to enable parts of the deforming till to agglomerate into stable nuclei on the glacier bed the till must be dewatered to some extent: otherwise deformation would continue owing to the incompressible nature of water. This problem was not considered by Boulton *et al.* (1974) or Muller (1974) in their analysis of the implications of subglacial deformation of till.

If this situation pertained beneath the ice, then it suggests that deformation and agglomeration of the till was just an initial event in the creation of the ridges; for the escape of subglacial water may eventually have had a reverse effect on the process of deformation. Its escape would tend to reduce the "buoying" effect of the water pressure and in turn increase effective pressure which would inhibit dilatancy. Such a sequence of events would thus effectively protect the already formed agglomerated till from further deformation as well as promoting lodgement of till around the

"proto-ridges". Boulton (1974, 1975a) has emphasised that at critical normal pressures abrasion ceases and complete lodgement of till occurs. It seems possible therefore that removal of excess sub-glacial water may have created such conditions in the Carsphairn area.

Problems still arise, however, especially in explaining why certain ridges maintained their elongate form. This may be related to the interaction of various factors such as the frictional resistance offered by the agglomerated till, which would have encouraged lateral build-up by pressure melting. The "beaded" form of many of the ridges also suggests coalescence of adjacent "proto-ridges", which would again aid elongation of the forms. Finally, the location of the ridges with reference to the former ice-shed and local topographic controls would also mean that the ridges would not have had to withstand the rigours of over-riding by powerful ice streams and this would have helped maintain their cross-valley form at the glacier bed, as opposed to the usual streamlined forms that are characteristic of active ice.

The termination of all except two of the cross-valley ridges both at the valley axis and below 275 m O.D. may also be explained by this hypothesis. The distribution of Cairnsmore of Carsphairn granite, Craig of Knockgray microgranite and Caradocian conglomerate erratics shows, at least in the area SE of the former ice-shed (where the ridges are best developed), discrete paths that have their margins along the valley axis. For example, the granite and microgranite erratics mentioned above are not found to the SW of the Water of Deugh (Chapter 5, Figures 5.4, 5.5). This suggests that ice flow patterns and therefore the ridge-forming process were operating

independently on opposite sides of the valley. Support for this view is found in the observation that most of the ridges attain their best development at the valley axes, but are abruptly truncated at this point. A sudden termination of the ridge-forming process is thus implied; otherwise a decline in their morphological expression might have been expected towards the centre of the valley. In addition, the subglacial escape route for excess porewaters, argued for above, may have contributed to ridge termination at the valley-axis by preventing further elongation of the ridges across the valley axis.

Above 275 m O.D., however, escape routes for excess porewater were largely absent and therefore any till that was present continued to deform and was eventually deposited either as amorphous lodgement till or by pressure melting against upstanding bedrock knolls to produce the lee-side drumlins (26, Figure 7.7) and crag-and-tail forms (25, Figure 7.7) that occur on the NW slopes of Bardennoch Hill.

12.5 SUMMARY AND CONCLUSIONS

The morphological characteristics and landform associations of the cross-valley ridges located in the Carsphairn area bear a close resemblance to the ribbed/Rogen moraine landforms described by various Canadian and Scandinavian workers and it is suggested that the former are genetically related to them. The literature review indicates three main hypotheses for the environment of deposition of these landforms: frontal, supraglacial and subglacial. Evidence presented in earlier chapters suggests a subglacial origin for the Carsphairn cross-valley ridges. This interpretation is based on:

- 1) their morphological and sedimentological association

with drumlin and drumlinoid landforms.

- 2) the absence of stratified sands and gravels in the till composing the cross-valley ridges.
- 3) the high silt content and generally indurated nature of the till in the ridges.
- 4) the general lack of continuity of the ridges across the valley and their non-arcuate form.
- 5) their position with respect to the former ice-divide zone in the area.

In terms of ridge formation in a subglacial environment, the literature review shows that three mechanisms have been proposed: squeezing, shearing and undulating ice flow. It is argued that none of these mechanisms provides entirely satisfactory answers to the problem of their formation and an alternative hypothesis is suggested that explains many of the unanswered questions about these landforms. This hypothesis is based on a combination of four inter-related factors.

- 1) Ice condition: the temperate-based nature of the ice-sheet, provided subglacial water and the influence of the ice-sheet restricted debris evacuation owing to the low ice velocities.
- 2) Local topographic controls: the basin-like nature of the area in which the ridges occur also allowed the build-up of debris in the area.
- 3) Bedrock geology: the low permeability of the greywacke bedrock encouraged the development of high subglacial water pressures in the area.

- 4) The physical state of the till at the base of the ice: the environment of deposition and composition of the till made it susceptible to deformation and agglomeration into "proto-ridges" upon dewatering.

Since the evidence presented on the cross-valley ridges indicates formation subglacially and as they are closely related to the extensive Galloway drumlin field it is suggested that they were formed when ice of considerable thickness occupied the area.

CHAPTER THIRTEEN
THE LOCH LOMOND ADVANCE IN
THE WESTERN SOUTHERN UPLANDS

13.1 INTRODUCTION

Although it has long been recognised that, following the decay of the Late-Devensian ice-sheet, local glaciers developed in the hills surrounding the Loch Doon basin, these have not been delimited in detail. This chapter describes the morphological evidence that defines eleven former glaciers interpreted as having existed during the Loch Lomond Stadial (Figure 13.1). Relict periglacial landforms are also described and some palaeoclimatic inferences and comparisons made.

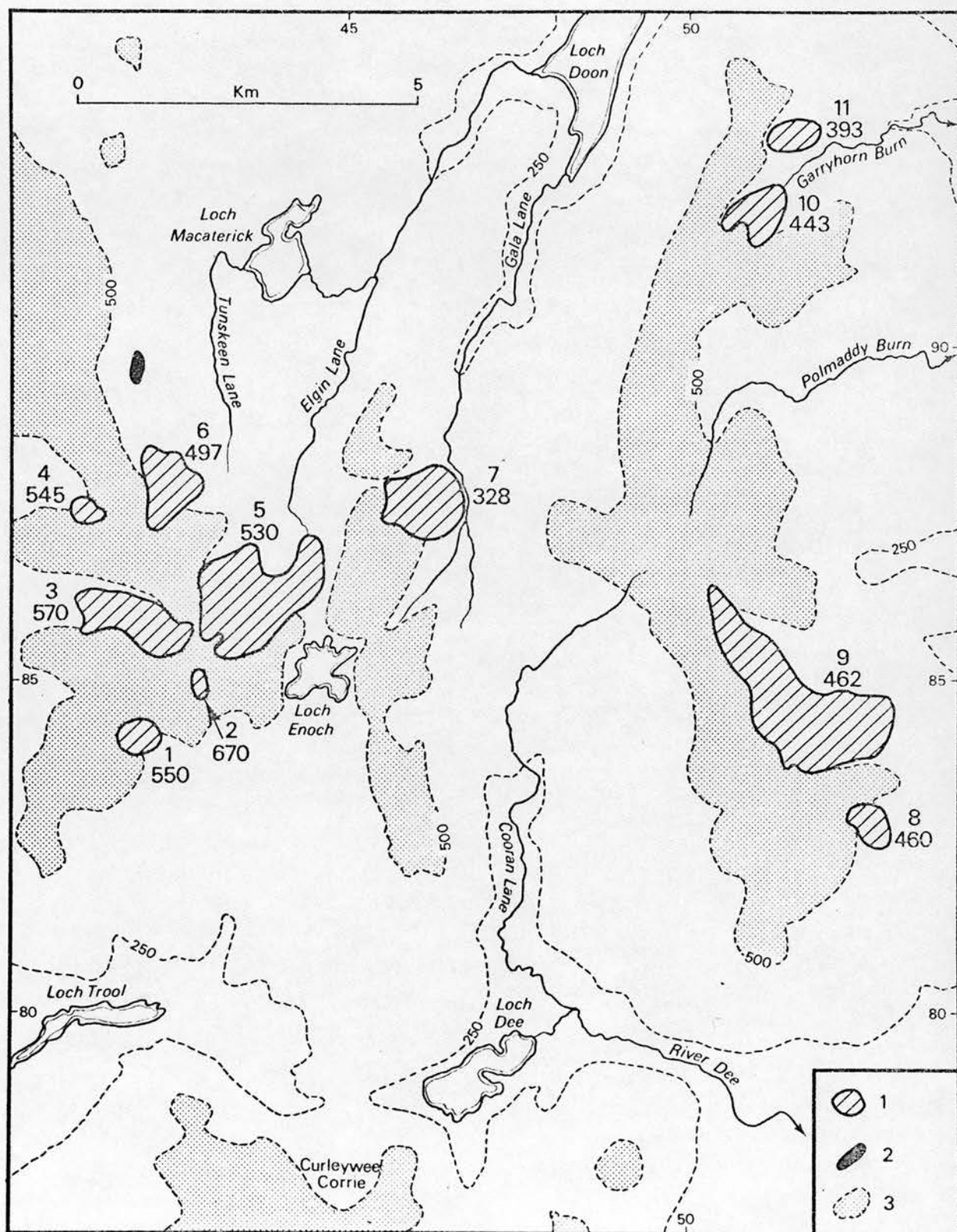
13.2 LITERATURE REVIEW

A. Geikie (1863) commented on the probable existence of small groups of glaciers in Galloway, particularly around the Merrick, while Jolly (1868) identified the impressive moraine located by Loch Dungeon (glacier 9, Figure 13.3C). More recently, Charlesworth (1926a), Moar (1969) and Sissons (1976) have made passing reference to the massive end moraine in the lee of Mullwharchar (glacier 7, Figure 13.3A). Charlesworth (1926a) also drew attention to the moraines on the lower slopes of Kirriereoch and Merrick, equating them with his "corrie moraine" stage.

Pollen analyses of cores recovered from various parts of the Loch Doon basin and surrounding hills have been reported by Moar (1969)

Figure 13.1 **Extent of Loch Lomond Advance glaciers in the**
W-C Southern Uplands; the equilibrium firn
line altitudes of each of the 11 former glaciers
are indicated.

- 1) Glaciers**
- 2) Landslide**
- 3) Land above 500m.**



and Birks (1972). Moar sampled sites in the Nick of Curleywee corrie and from the peat bog behind the double end moraine by Mullwharchar. Moar's mapping of the former area has already been shown to be suspect (Chapter 6) and thus his statement that "... the Zone IV sediments impounded behind the moraine at Nick of Curleywee implies that at this site ... Upper Dryas glaciers were restricted to corrie basins" (1969, p.466), is erroneous. The core recovered from the Mullwharchar moraine (Tauchers) comprised 4.8 m of detritus mud and fibrous peat underlain by 20 cm of blue-grey silty clay. Although Moar presented no pollen diagram for the site, he suggested that the moraines may have been related to "... glacial conditions during the Late Weichselian" (1969, p.466).

Birks (1972) looked at cores from sites by Snibe Bog, in the Cooran Lane trough, and from the bottom of Loch Dungeon (behind the end moraine). Only early Flandrian and younger pollen were identified: Birks noted the occurrence of moraines in corries and therefore suggested that the Loch Lomond Stadial glaciers were not extensive in Galloway.

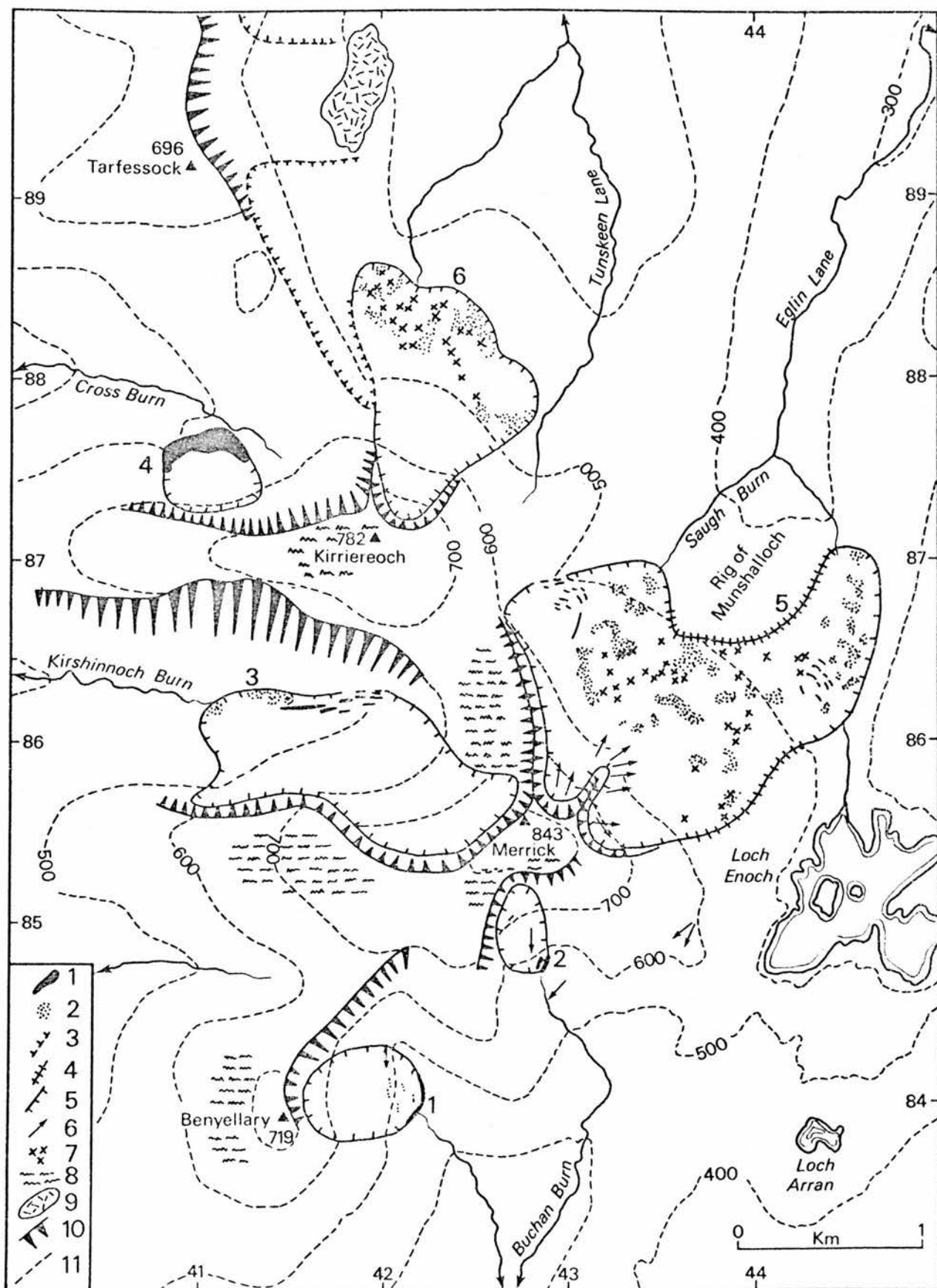
13.3 LIMITS OF THE FORMER GLACIERS

The principal morphological evidence from which the former glaciers have been reconstructed is shown in Figures 13.2 and 13.3.

Glacier 1: The limit is defined by a rampart of till some 5 m high that stands above an ice-scoured bedrock ledge at the corrie lip (Plate XIII). The proximal slope is less well developed (2 - 3 m high) owing to the mass of drift situated within the limit.

Figure 13.2 **Former glaciers and fossil periglacial features**
in part of the W-C Southern Uplands. The key
also applies to Figure 13.3 A, B, C.

- 1) End moraines and other prominent linear morainic ridges.
- 2) Hummocky moraine.
- 3) Boulder limit.
- 4) Drift limit.
- 5) Other ice limit.
- 6) Striae.
- 7) Metamorphosed greywacke erratics.
- 8) Fossil periglacial features.
- 9) Landslide.
- 10) Very steep slopes, mainly of glacier source areas.
- 11) Contours on land and former glacier surfaces at 100 m intervals.



The latter lacks any constructional form and in plan view comprises an oval-shaped mass that occupies the floor of the corrie. Spreads of granite and graywacke boulders cover the surface of the drift. The very steep rock wall cut into the eastern face of Benyellary compared with the adjacent sides of the corrie indicates that glacier accumulation was not symmetrically distributed here and the limit has been interpolated accordingly (Figure 13.2).

Glacier 2: A rather ill-defined end moraine, comprising two short ridges (100 m in length) marks the former glacier terminus. Behind the moraine bedrock is exposed extensively.

Glacier 3: The northern margin is recorded by lateral moraines, 2 - 3 m high, on the floor of the Kirshinnoch trough. The limit is continued to the west by hummocky moraines, 3 - 4 m high, that are littered with granite and graywacke boulders. There is no end moraine and thus the western limit of mounds is interpreted as the glacier terminus (cf. Sissons 1977).

Glacier 4: A broad, arcuate end moraine damming up Balminnoch Loch marks the former glacier limit. It is located on a bedrock bench that slopes quite steeply to the west. The moraine extends continuously for 650 m and the distal slope is 3 m high. The whole complex is 130 m wide, is littered with granite boulders up to 2 m in diameter, and comprises a series of interconnected ridges (1 - 2 m high) and depressions that follow the arcuate trend of the moraine (Plate XIV).

The moraine disrupts a series of massive E-W-trending till ridges (described in Chapter 6) that are interpreted as being related to the

Late Devensian ice-sheet. The unusual width of this moraine in relation to the size of the former glacier can therefore be attributed to the abundant debris available in these pre-existing ridges.

Glacier 5: This former glacier had its source in the two corries cut in the eastern face of Merrick and possessed two terminal lobes separated by a bedrock ridge. A distinct drift limit descending from 600 m to 500 m defines the southern margin of the more easterly lobe, while another extending from 490 m, on the crest of Rig of Munshalloch, to 430 m marks the NW margin of the same lobe. Within these limits are elongated hummocky moraines 3 m high and averaging 50 m in length. Some are randomly orientated, some parallel the direction of former ice movement as shown by striae, while others are arcuate in form, extending across the Caldron Burn Valley. Sections in the hummocks reveal a friable till with a gritty matrix. The hummocky moraines are strewn with boulders of both granite and greywacke. The presence of the latter (discussed in Chapter 5) signifies a reversal in the direction of former ice movement from the radial flow of the ice-sheet to the localised movement into the Loch Doon basin that characterised the Loch Lomond Advance glaciers. These erratics thus help define the limit of the former glacier, which in the absence of an end moraine is placed at the limit of hummocky moraines and greywacke boulders (Figure 13.2).

The margins of the western lobe are poorly defined: here the eastern limit of hummocky moraine (littered with granite boulders) and metamorphosed greywacke erratics is interpreted as the former glacier terminus. A series of small, but impressive, moraines 3 - 4 m high encircles Loch Twachtan at the head of the Saugh Burn



Plate XIV: Terminal moraine of Loch Lomond Advance glacier 4
(Figure 13.2) by Kirriereoch. Note drumlinoid ridges
of the Late-Devensian glaciation in the background.



Plate XVI: Medial moraine of Loch Lomond Advance glacier 9
(Figure 13.3C) by Loch Dungeon.

valley. The close proximity of these features to those associated with the northern lobe of glacier 5 implies that the two glaciers coalesced and such a limit is plotted on Figure 13.2.

Glacier 6: This glacier was nourished in a corrie cut in the NE face of Kirriereoch hill. Its western margin is defined by a boulder limit (comprising granite blocks) that leads out from the corrie mouth (550 m O.D.) and continues downslope to 470 m O.D. where it disappears beneath extensive blanket peat (Figure 13.2). The corrie lacks granite boulders but the hummocky moraine on the lower ground to the north are strewn with them. Elongated till ridges beyond the hummocky moraine lack granite boulders, thus enabling the terminus of the former glacier to be defined. The eastern margin is defined by the limit of metamorphosed greywacke erratics and by hummocky moraines.

Glacier 7: This glacier was nurtured in a corrie-like embayment between Mullwharchar and Hoodens Hill (Figure 13.3A). Its terminus is delimited by an eastward-facing double end moraine complex (Plate XV). The outer moraine, 1.6 km long, is 200 m broad at its widest point, narrowing to 50 m towards the north. Its steep distal slope has been trimmed and sharpened by the Gala Lane, which has also produced sections that displayed an olive-brown, sandy till rich in boulders. The moraine reaches its maximum height (10 - 12 m) at the southern end where it comprises a series of ridges and depressions with an amplitude of 2 - 3 m. From here the moraine gradually declines in height northwards to a minimum of 5 - 6 m, where it becomes increasingly covered with angular boulders of granite at the expense of the till matrix. Above 275 m O.D. well-developed twin, lateral boulder moraines (corresponding to the proximal and distal

Figure 13.3 A, B, C. Former glaciers and periglacial
features in part of the W-C
Southern Uplands.

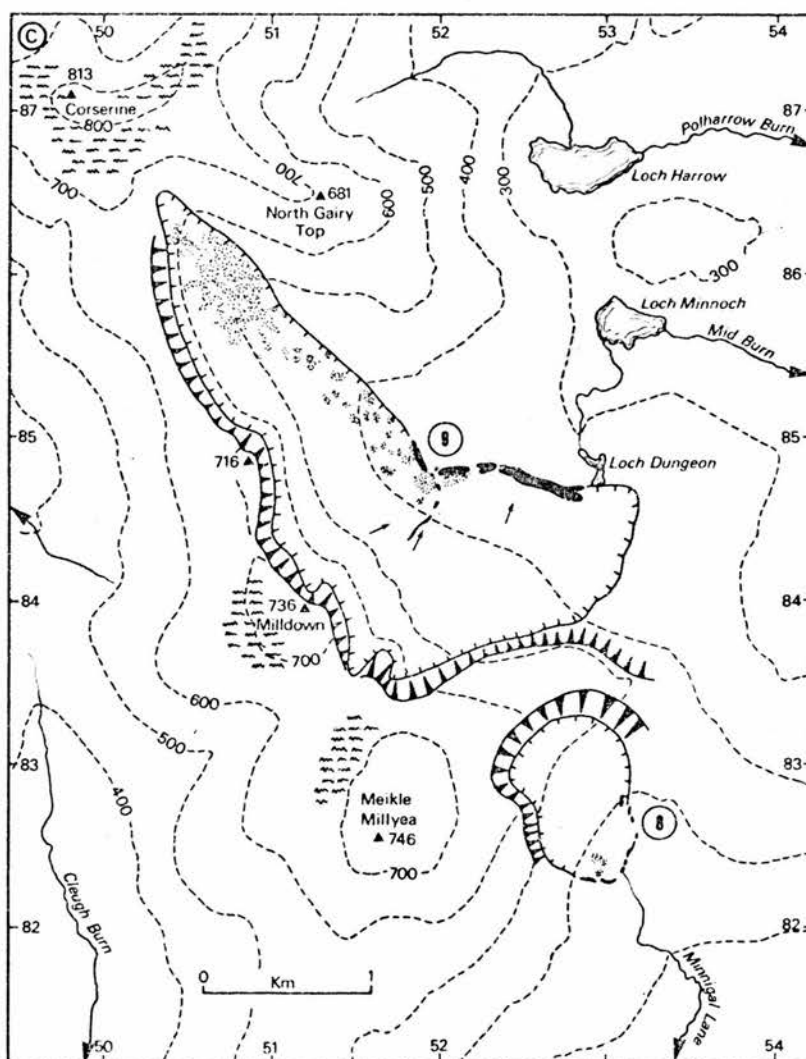
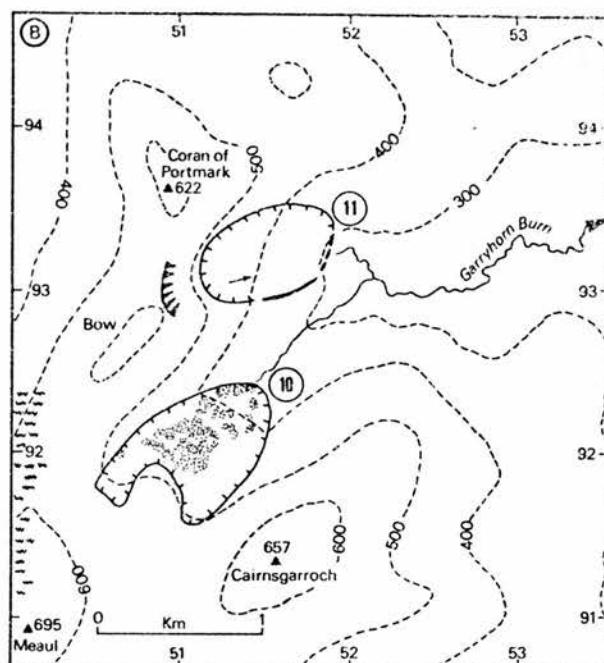
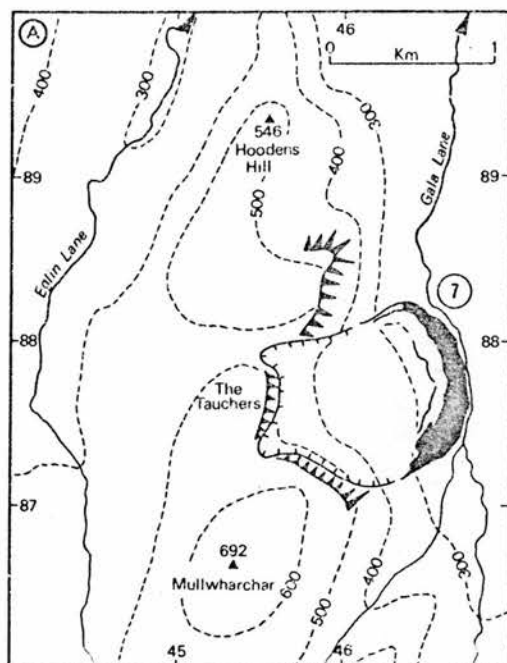




Plate XV: Aerial photograph showing the double end moraine complex of Loch Lomond Advance glacier 7 (Figure 13.3A) by Mullwharchar. (Crown copyright reserved).

slopes of the outer moraine) curve round to the west and climb the steep rock wall of Yellow Tomach, terminating at 290 m and 335 m O.D. respectively. These laterals comprise huge angular granite blocks up to 5 m in diameter resting in a jumbled fashion upon one another. They are not, however, developed at the southern margin, where a till ridge with included granite boulders is the main feature. This extends upslope to ca. 335 m O.D. where it terminates against the almost vertical north face of Mullwharchar. The several ridges comprising the moraine, which parallel its curvature, suggest an oscillating ice front.

The inner moraine lies between 50 m and 150 m west of the outer moraine. It is a delicate, sinuous feature composed of olive-brown sandy till, is 3 - 5 m high, up to 10 m wide and 1.1 km long. Its northern margin is continued upslope to 335 m O.D. by an impressive boulder lateral which closes with, but does not join, the boulder lateral associated with the proximal slope of the outer moraine. At the southern margin the moraine merges with the above mentioned intermediate ridge; no laterals are present here.

Glacier 8: The end moraine defining the former snout extends intermittently for 600 m across the lip of the SE-facing corrie and comprises a single ridge 2 - 3 m high. Two small fragments of a lateral moraine mark the NE margin at 380 m O.D. Inside the limit, the corrie floor is mainly peat-covered although bedrock crops out in numerous places. Drift deposits are confined to a small patch of elongated hummocky moraines by the SW margin.

Glacier 9: This former glacier was confined to the large, NE-facing

corrie cut into the eastern slopes of the Rhinns of Kells range. The floor of the NW section of the corrie is occupied by "text-book" hummocky moraines. Many of the mounds are conical in form and reach 8 m in height, while others are more elongated, trending NW-SE. They are composed of friable, sand/silt-rich till and are littered with metamorphosed greywacke boulders. The NE margin of the former glacier at this point is placed where the hummocky moraines terminate against massive valley-fill deposits occupying the SE slopes of North Gairry Top: the latter are sharply truncated where they meet the hummocky moraines.

To the SE a well-defined medial moraine commences at the foot of the precipitous rock wall below Milldown summit and extends for 320 m to the NE (Plate XVI). It is asymmetrical in cross-profile, being 10 m high on the SE side and 5 m high on the NW. Sections in the feature where it has been cut through by Hawes Burn showed a friable, sand-rich till with only a few boulders.

A large end moraine marks the NE margin of the former glacier in the SE part of the corrie. The feature extends almost continuously for 1 km, has a proximal slope up to 8 - 10 m high, and partly dams the eastern basin of Loch Dungeon. The moraine crest is broad (up to 80 m wide) and littered with numerous blocks of metamorphosed greywacke, some attaining 4 m in diameter.

Glacier 10: The down-valley termination of a belt of hummocky moraines delimits the snout of the former glacier. Within the limit the hillside is covered by a suite of generally elongated ridges composed of friable, sand/silt-rich till. The NW margin is defined by the termination of these features.

Glacier 11: An end moraine 3 m high records the terminus of the former glacier. This extends upslope as a lateral moraine to 380 m O.D. where it defines the southern margin.

13.4 PERIGLACIAL FEATURES

Periglacial features were mapped in the same way as glacial landforms. No detailed analyses or investigations of them were attempted since the major interest lay in their distribution. Both fossil and active forms were observed and these are considered in the two sections below.

Fossil periglacial phenomena

Periglacial features are extensively developed on the higher parts of the Scottish Highlands (Galloway 1961a,b; King 1972; Sissons 1974b) and they have also been recorded from various parts of the Southern Uplands. For example, A. Geikie (1863) recognised solifluction material in upland Berwickshire and differentiated it from primary till deposits. Galloway (1961b, p.77) stated that solifluction deposits form "only a thin skin less than a couple of feet thick on the hills, becoming somewhat deeper at the foot of long slopes but not extending far out from the valley sides". Solifluction debris 3.5 m thick was described by Ragg and Bibby (1966) from Broad Law, while Tivy (1962) found fossil "head" 1 m thick on the slopes of the Lowther Hills.

In the study area the major periglacial landforms are restricted to ground outside the limit of the Loch Lomond Advance glaciers (cf. Sissons and Grant 1972; Sissons 1974a, 1979a). Even in corries

at altitudes above 850 m they do not occur within the former limits despite the abundance of boulders. Further, there is a growing body of evidence to suggest that the large fossil periglacial features in Scotland were a product of the extremely severe climatic conditions that existed during the Loch Lomond Stadial (Sissons 1974b, 1976). That solifluction occurred at low altitudes in the western Southern Uplands and adjacent areas at this time is suggested by the minerogenic sediments in Lateglacial pollen and coleopteran sites (Godwin *et al.* 1957; Moar 1969; Bishop and Coope 1977). The site investigated by Moar (1969) and Bishop and Coope (1977) is located at Bigholm Burn, by Langholm, Dumfriesshire (at only 160 m O.D.), which lies 85 km east of the study area. Here, Bishop and Coope described a sub-angular solifluction gravel overlain by an organic mud. Radiocarbon dates of $9,590 \pm 170$ B.P. and $9,470 \pm 170$ B.P. (Godwin and Willis 1964) from the latter deposit strongly suggest the gravel is of Loch Lomond Stadial age. Further evidence for solifluction processes acting at low altitudes is provided by a series of radiocarbon dates (11,650 to 11,150 B.P.) for peat overlain by soliflucted till in the Glasgow area (Dickson *et al.* 1976). Similarly, Rose (1975) has argued that the fossil frost wedges located in beach gravels at Old Kilpatrick on the Clyde date from the Loch Lomond Stadial.

Additional evidence for the severity of climate during the stadial comes from the Bigholm Burn site mentioned above. An organic silt layer interbedded with the upper parts of the solifluction gravels yielded only a very limited range of coleoptera, but these indicated conditions approaching that of "polar desert" (Bishop and

Coope 1977). The fauna was interpreted as of Loch Lomond Stadial age and as indicating that at this time average July temperatures were well below 10°C. These results are in accord with pollen analysis on the same material carried out by Moar (1969).

The results of periglacial processes in the study area are most evident on the mountain summits and upper parts of the glacial troughs, those areas where climatic conditions were at all times the most severe. On the NW slopes of Merrick above an altitude of 625 m massive, partly vegetated debris lobes mantle the hillside (Figure 13.2). The risers average 3 m in height and the lobes comprise boulders of greywacke and granite up to 0.75 m in diameter set in a gritty matrix. These features terminate abruptly at the northern margin of glacier 3 (Figure 13.2) and are not found within the limit, even though ground conditions are identical.

On the south-facing slopes of Merrick, small turf-banked terraces and lobes are well developed above 650 m O.D. (Figure 13.2). The risers are normally 0.5 to 0.75 m high, while the treads average 1.5 m in width. Similar forms occur on the west-facing summit slopes of Banyellary and the south-facing slopes of Kirriereoch (Figure 13.2) above an altitude of 650 m. Turf-banked terraces are again present by Corserine summit (Figure 13.3C) as well as on the west-facing slopes of Milldown, Miskle Millyea (Figure 13.3C) and Meaul (Figure 13.3B).

Galloway (1961a,b) stated that greywacke bedrock is too fissile to produce blockfields but recorded their presence on the granite areas of the SW Southern Uplands. Blockfields (*sensu stricto*) do not occur, however, on the Loch Doon granite mass, although in

numerous locations large, detached granite blocks litter the sides of U-shaped troughs. Their distribution is never of sufficient density to warrant the term block slopes for vegetation and bedrock often occur between them.

The granite blocks are best seen in the Cooran Lane - Gala Lane glacial troughs, especially on the east-facing slopes of Craignaw, Dungeon Hill and Hoodens Hill. Here boulders exceeding 5 m in diameter are not uncommon, though they normally average 2 m. Glacier 7 had its source area in this section of the trough (Figure 13.3A). The area behind its outer moraine, however, is almost devoid of granite boulders, those that are present having apparently rolled down from the slopes above, which were outside the limit.

Extending for a distance of 3.5 km north of Kirriereoch, the east-facing slopes of the Merrick range are covered with thousands of granite boulders. This mantle is continuous except where it has been disrupted by a landslide (see below) and it ends at the western margin of glacier 6 (Figure 13.2). The upper altitudinal limit of the boulder spread defines the granite/metamorphosed greywacke contact, which varies between 550 m and 590 m O.D. in this area.

The absence of blocks from within the areas formerly occupied by the Loch Lomond Advance glaciers and their incorporation into lateral and hummocky moraines produced by these glaciers suggests that such blocks were detached from the bedrock by the intense freeze-thaw processes that operated during the severe climatic conditions of the Loch Lomond Stadial.

A former landslide on the western side of the Loch Doon basin (Figure 13.2) has left a steep east-facing rock scar below the summit

of Tarfessock. The slipped mass is a single block of rock 650 m long and 250 m wide that rises up to 15 m above the surrounding peat cover. It is composed entirely of metamorphosed greywacke rock and rests on the lower slopes of Tarfessock at 400 m O.D. indicating a total movement downslope of some 200 m. The volume of the slide is estimated to be 1,600,000 m³. The distribution of granite boulders mentioned above helps delimit the descent path of the rock mass (Figure 13.2). To the north and south of this path the east-facing slopes are littered with boulders, but within it granite boulders are absent, but they occur farther downslope where they cover the slipped mass and the ground to the east.

The landslide post-dates the production of the boulder spread. As it has been argued that the detachment of the adjacent granite blocks occurred during the Loch Lomond Stadial then it is not unreasonable to suggest that frost wedging along joint planes during the stadial was a potent factor in the production of the landslide.

Active periglacial phenomena

Evidence for contemporary periglacial processes was found only on the very summits of Merrick (843 m) and Corserine (813 m). Here small-scale and rudimentary sorting of surface debris was observed, producing incipient stone polygons and poorly developed stripes. The processes, however, appear to be merely reworking material produced initially by frost-shattering during the Lateglacial. These features were previously commented on by Gregory (1927) who described them as "embryonic frost-formed stone polygons".

13.5 RECONSTRUCTION OF THE FORMER GLACIERS AND THEIR CHARACTERISTICS

The 11 glaciers shown in Figure 13.1 were all nourished on high ground (the majority in corries) and indicate a renewal of glacial conditions following the decay of the last ice-sheet. The methods used to reconstruct these glacier limits follows the guidelines given by Sissons (1974a, 1977). Reconstruction was facilitated by 7 of the 11 glaciers having produced terminal moraines and by all but one (glacier 5) having single source areas.

The glacier surfaces were contoured at 50 m intervals, but for clarity only the 100 m interval is shown in Figures 13.2 and 13.3. Contouring was carried out after reference to contour maps of modern glaciers. Contours are normally convex down-valley close to glacier snouts, trend straight across glaciers in their middle parts and are usually convex up-valley in their source areas: hence contours on the Loch Lomond Advance glaciers were drawn in this manner. Account was also taken of the gradients of the beds of the former glaciers.

Table 13.1 shows various parameters derived for the glaciers. Glacier areas were obtained by superimposing a grid of squares with side equivalent to 100 m onto the 1:25,000 map. The total measured area occupied by the glaciers is 9.92 km^2 , of which 3.18 km^2 (32 per cent) is accounted for by the Loch Dungeon glacier (glacier 9).

Glacier volumes were derived using a rectangular grid of sample points spaced at distances equivalent to 50 m, 75 m or 100 m depending on glacier size. Ice thickness is given by the difference in altitude between glacier surface and the underlying glacier bed (taking into account peat thickness so far as practicable). The total measured volume of ice was 0.36 km^3 , of which 0.161 km^3 was provided

Table 13.1 Data relating to the Loch Lomond Advance glaciers in the western Southern Uplands.

Glacier number	Glacier area km ²	Glacier volume km ³	Maximum depth m	Lowest altitude m	Equilibrium firn line m	Insolation factor	SW	SE	NW	NE
1	0.29	0.008	75	435	550	14.7	0.38	0.00	0.51	0.52
2	0.12	0.002	30	550	670	16.6	0.41	0.00	1.74	1.17
3	0.98	0.036	95	425	570	12.6	0.17	0.29	0.00	0.26
4	0.19	0.002	20	495	545	12.2	0.60	1.57	0.00	1.05
5	1.99	0.051	65	410	530	12.5	0.30	0.00	0.24	0.01
6	0.88	0.026	55	410	497	11.6	0.74	0.07	0.33	0.00
7	0.91	0.03	70	250	328	13.9	1.05	0.16	0.63	0.00
8	0.52	0.019	95	355	460	15.9	1.18	0.00	0.95	0.07
9	3.18	0.161	140	310	462	14.4	0.35	0.28	0.22	0.28
10	0.49	0.012	45	330	443	11.5	2.22	1.46	0.94	0.22
11	0.37	0.010	65	295	393	12.4	1.96	0.00	0.92	0.41

by the Loch Dungeon glacier, which also possessed the greatest ice thickness (ca. 140 m). The dominance of the Loch Dungeon glacier was a function of the massive corrie in which it was nourished compared with those in other parts of the area (Figure 13.1).

The equilibrium firn line altitude for each glacier, at its maximal extent, was calculated on the assumption that the ablation gradient and accumulation gradient are each linearly related to altitude. The equation provided by Sissons (1974a), which is based on the area of the glacier surface between successive contours, was used. Values derived range from 328 m (glacier 7) to 670 m (glacier 2), with a mean of 495 m.

An indication of the potential influence of direct insolation, under clear-sky conditions, on each of the former glaciers was calculated for the probable ablation season (May - September) using the method described in Sissons and Sutherland (1976). The value obtained for each glacier is referred to as its insolation factor. The calculation takes into account the aspects and gradients of the glacier surfaces, the albedos of ice and snow and the transmissivity of the atmosphere. For a horizontal glacier the value is ca. 13.7 at $55^{\circ}10' \text{ N}$ (the latitude used for the calculation) and the values for individual former glaciers range from 11.5 (glacier 10) to 16.6 (glacier 2). A high insolation factor for a glacier indicates that it was located adversely since it could absorb a large amount of direct insolation. The insolation factor does not give absolute values of direct radiation received, for the extent of former cloud cover is unknown. However, in a small area like the western Southern Uplands it does give a measure of the relative amounts of direct

insolation absorbed by the glaciers.

Another important factor influencing glacier altitude is the amount of snow blown onto a glacier from adjacent higher ground. An indication of the influence of this factor was obtained by measuring potential snow-blowing areas on the 1:25,000 O.S. map, after eliminating the areas of avalanching potential (slopes over 20° leading directly down to the former glaciers above the firn line), using the arbitrary rules outlined in Sissons and Sutherland (1976). The values for each quadrant were calculated: thus, for example, the potential snow-blowing area for the SW quadrant refers to all points that can be connected to a glacier surface above the firn line by a straight line with a continuous downhill slope along the ground surface from directions between 180° and 270° . Overlaps occur between adjacent quadrants and therefore ground located, for example, due south of a glacier will be included in both the SE and SW quadrants. Table 13.1 presents the derived potential snow-blowing areas as a ratio of the respective glacier area.

13.6 PALAEOCLIMATIC IMPLICATIONS AND COMPARISONS

The present precipitation in the western Southern Uplands is high on the N-S-orientated mountain axes of the Merrick range, the Hoodens Hill - Mullwharchar - Cragshaw range and the Rhinns of Kells, in parts of which it exceeds 2500 mm a year (Bown 1973). Precipitation amounts diminish rapidly, however, towards the surrounding low ground, being only 1500 mm at Carsphairn (180 m O.D.) due to the rain shadow effect and 1100 mm at Girvan (30 m O.D.) on the coast.

In view of this pronounced orographic influence it is difficult to envisage a distribution of precipitation during the Loch Lomond Stadial that was not strongly governed by relief. All the glaciers are contained within the three above-mentioned mountain ranges (Figure 13.1), 45 per cent of the total glacier area being in the Merrick range and 46 per cent in the Rhinns of Kells. No regional trend of firn line altitudes of former glaciers exists in the western Southern Uplands, which suggests that other factors exerted a strong control on firn line altitude. It is believed that such factors include the effects of direct insolation and snow blowing, both of which are considered below.

All glaciers in the western Southern Uplands have relatively high insolation factors (mean insolation factor = 13.5), which indicates that, in general, the glaciers were adversely located. In particular the unfavourable location (facing south and SE) of glaciers 2 and 8 in terms of direct insolation is shown by their factors of 16.6 and 15.9 respectively, compared with which adjacent glaciers 3 and 5 (facing north and NE), with factors of 12.6 and 12.5 respectively, occupied more favourable locations.

Similar contrasts obtain in glacier size, with five of the seven glaciers with aspects between north and east (3, 5, 6, 7, 9) having volumes larger than those (2 and 8) that faced south and SE ($0.026-0.161 \text{ km}^3$ as opposed to 0.002 km^3 and 0.019 km^3). The first mentioned glaciers also possess lower insolation values, which suggests that direct insolation influenced glacier size to a considerable degree.

Variations in direct insolation cannot, however, explain the

reduction in glacier size in the NE part of the Loch Doon basin, for glaciers 10 and 11 have low insolation factors and have aspects between north and east. Latitudinal differences in temperature would not have been significant in such a small area and therefore it is suggested that differences in former snowfall in the Loch Doon basin were in part responsible, with lower snowfall in the NE, due to the orographic effect, than in the south and SW. This pattern accords with the apparent absence of a former glacier from the north-facing valley-head embayment occupied by Polmaddy Burn (Figure 13.1) as well as with the present-day differences in precipitation, which are lower in the NE (Bown 1973).

It is evident from the measurement of potential snow-blowing areas on the 1:25,000 U.S. maps that several glaciers occupied sites where the transfer of snow by wind from surrounding higher ground was an important factor in their nourishment. Some of the firn line altitudes that are very low in relation to adjacent ones may be partly explained in this way. Manley (1959) and Sissons (1979c) have emphasised this point in their studies of Loch Lomond Advance glaciers in the Lake District and Cairngorms. The low firn line altitudes of glaciers 10 and 11 (443 m and 393 m), besides being influenced by reduced precipitation amounts, can also be partly attributed to the transfer of snow from adjacent high ground. The SW snow-blowing areas for these glaciers are respectively 2.22 and 1.96 times as large as the glacier areas, compared with the mean value for all glaciers of 0.85. Glacier 7, with its firn line altitude of 328 m (the lowest in the area) was similarly influenced; its SW snow-blowing area is 1.05 times as large as the glacier area. The SW snow-blowing ratio for glacier 8 is 1.18 times that of its area. This glacier, as

mentioned above, was adversely located in terms of direct insolation received (insolation factor of 15.9) and yet the firn line is relatively low (460 m) compared with others in more favourable locations. Thus it seems likely that, without the contribution from snow-blowing, this glacier would have been much attenuated in size (cf. glacier 2 where the SW snow-blowing ratio is only 0.41) or may not have existed.

These examples suggest an inverse relationship between snow-blowing areas and firn line altitudes. This relationship was tested for the 11 glaciers using correlation analysis (Norcliffe 1977). Analysis of the SE, NW and NE snow-blowing quadrants against firn line altitudes showed no correlation, but for the SW quadrant the relationship is significant at the 0.05 level ($r = -0.822$). The importance of snow transfer by wind from the SW quadrant has also been found from investigations of Loch Lomond Advance glaciers in the Lake District, the SE Grampians, the Cairngorms and NW Highlands (Sissons 1979c; Sissons and Sutherland 1976). Thus the results from the western Southern Uplands lend further support to Sissons' view that SW winds were important in transferring snow to glaciers during the Loch Lomond Stadial.

Finally, the very small areal extent ($\Sigma = 9.92 \text{ km}^2$) and volume ($\Sigma = 0.36 \text{ km}^3$) of the former glaciers in the western Southern Uplands throws considerable doubt on the limits proposed by Gemmell (1973) for Loch Lomond Advance glaciers on the Isle of Arran. He suggested that two glaciers in the northern hills reached "tidewater" during the Loch Lomond Stadial, but more likely "... the several moraines with a fresh appearance in the corries of the higher hills" (Gemmell 1973, p.35), which are above 450 m O.D., represent the former

Loch Lomond Advance glacier limits on Arran.

13.7 SUMMARY AND CONCLUSIONS

The extent of 11 glaciers that existed in the western Southern Uplands during the Loch Lomond Stadial has been inferred from evidence of terminal and hummocky moraines and glacial erratics. The most favourable aspect for glacier development was between north and east where the effect of direct insolation was much reduced. Hence glaciers were larger in these locations. Glaciers whose accumulation areas faced south or SE had high insolation factors and were smaller. The firn line altitudes of certain glaciers were influenced by the transfer of snow by wind from adjacent high ground, with the SW quadrant being particularly important in this respect. It has been inferred that the principal snow-bearing winds were from a southerly direction, with snowfall being higher in the SW part of the Loch Doon basin than in the NE. This result compares well with results from the Lake District and NW Highlands of Scotland.

CHAPTER FOURTEEN
GENERAL CONCLUSIONS AND
SUGGESTIONS FOR FURTHER RESEARCH

14.1 INTRODUCTION

From the basic aims of the present study set out in Chapter 1 six main conclusions have emerged and these are considered below. In addition, this study has raised a number of points that are relevant to the formulation of future projects of a similar nature and these are outlined in the latter part of the chapter.

14.2 THE FORM OF THE LATE-DEVENSIAN ICE-SHEET IN THE STUDY AREA

Loch Doon granite erratics occur on the summit of Merrick (843 m), which is the highest point in the study area (as well as in the Southern Uplands). If it is assumed that the mapped granite erratics were distributed by the last ice-sheet, then it can be inferred that the whole study area was ice covered during the Late-Devensian glaciation. This indicates a minimum altitude for the ice-sheet surface of 843 m. The exact altitude of the ice-sheet surface at the Late-Devensian maximum cannot be given. However, Sissons (1976) has estimated that the surface of the ice-sheet in the Western Grampians was ca. 1500 m. If this figure is approximately correct, 1200 m seems a reasonable estimate for the maximal altitude of the ice-sheet in the western Southern Uplands.

Glacial breaches and cols over-ridden by ice that cut through the hills surrounding the Loch Doon basin collectively display

a radial pattern, indicating that this area was not only a major zone of ice accumulation but also the main centre of ice dispersal in the western Southern Uplands. The widespread distribution of granite erratics over southern Ayrshire and Kirkcudbrightshire supports this interpretation. Ice flow from this centre was sufficiently powerful to deflect the Highland ice from its southward movement.

14.3 FORMER DIRECTION OF ICE-SHEET MOVEMENT IN THE STUDY AREA

In the Loch Doon basin the distribution of erratics and the trend of striae demonstrate a radial movement of ice, except to the east. The existence of a former ice-shed is also indicated, traversing the Loch Doon basin probably from the summit of Merrick in the west to Corserine in the east. Ice generally flowed north and south away from this zone in the centre of the basin, but farther west a westerly flow of ice prevailed.

In the Carsphairn Lane - Water of Deugh - River Ken area glacial erratics and ice-moulded landforms demonstrate that the above-mentioned ice-shed was continued to the east, probably via the summits of Cairnsgarroch, Craig of Knockgray and Cairnsmore of Carsphairn. Ice flow was to the NW or SE away from the ice-shed. Farther SE from the ice-shed, additional ice streams joined the main flow from the eastern flanks of the Rhinns of Kells, which deflected ice flow into a more easterly direction.

14.4 GLACIAL DEPOSITS OF THE LATE-DEVENSIAN ICE-SHEET IN THE STUDY AREA

A striking contrast obtains between the Loch Doon basin, where

glacial deposits are of limited extent (landforms of glacial erosion being dominant), and the Carsphairn Lane - Water of Deugh - River Ken through-valley where large-scale deposits of till occur, even astride the former ice-shed. Their absence in the former area indicates evacuation of the debris owing to the generally unrestricted nature of ice flow. The proposed explanation for the massive till accumulation within the ice-shed zone in the Carsphairn area is that debris was emplaced during ice-sheet build up; glaciers flowing from the hills on either side of the valley coalesced, but owing to their differing directions of flow, stagnation of the basal ice ensued. The debris thus emplaced remained in this position during the major part of the Late-Devensian, since its evacuation was prohibited by the ice-shed and local topographic controls. The termination of the Craig of Knockgray microgranite erratics train only 2.8 km from its source, the unusually wide arc through which its boulders are distributed, and the limited transportation of Caradocian conglomerate erratics accord with this view.

Two tills are exposed in the Carsphairn Lane - Water of Deugh - River Ken valley: these comprise an upper olive-coloured unit and a lower gray unit. They have been differentiated on the basis of their particle-size, roundness, geotechnical and lithological characteristics, and it is argued that these differences were controlled by the lithology of the local bedrock and the position of transport of the debris within the ice. Moreover, it has been argued on the basis of the sedimentological properties of the tills that they (and, by inference, the landforms composed of them) were deposited subglacially.

The olive till is present in an association of landforms that are

genetically related. Olive till with a valley-fill morphology merges down-ice into cross-valley ridge landforms, which pass into muted drumlins that are succeeded by "text-book" drumlins that form the NW part of the Galloway drumlin field.

The morphology and landform association of the cross-valley ridges suggests that they are related to the Rogen and ribbed moraines described from Scandinavia and Canada. Previous hypotheses presented for the formation of Rogen/ribbed moraines have been found to be unsatisfactory. An alternative hypothesis has been presented, which explains many of the problems associated with this type of landform. The postulated sequence of events in the formation of the cross-valley ridges of the Carsphairn area is as follows:

- 1) Debris was emplaced during ice-sheet build up and remained below the ice-shed that developed during the Late-Devensian glaciation.
- 2) At some unknown time after the ice-sheet maximum basal shearing by cleaner ice over-riding the debris-rich, basal layers initiated deformation and dilatancy in the latter material. Deformation was aided by high subglacial water pressures, associated with the impermeable bedrock, which served to reduce effective normal pressures exerted by the overlying ice.
- 3) De-watering of the till occurred in certain parts of the area causing the agglomeration of "proto-ridges" at the ice/bed interface. Excess porewaters escaped along a subglacial channel, which is now occupied by the Water of Deugh. Termination of the ridges at the valley axis and at ca. 275 m O.D. is also thought to relate to the availability of escape paths for excess porewaters.

- 4) The de-watering of the till increased effective pressures on the ice/bed interface, halting deformation, but enhancing pressure melting of till around the "proto-ridges" thereby promoting their elongation into a ridge form. In certain locations continued deformation streamlined the ridges into drumlinoid forms or drumlinised the surfaces of larger ridges.
- 5) Farther from the ice-shed increased ice velocity promoted the formation of drift and rock drumlins, the former being confined largely to topographic "lows" where excess porewaters could be dissipated.

Thus it is concluded that cross-valley ridge formation was controlled by a combination of factors, the most important being ice condition and velocity, bedrock geology, local topography and the physical properties of the till.

14.5 FLUVIOGLACIAL LANDFORMS ASSOCIATED WITH THE LATE-DEVENSIAN ICE-SHEET IN THE STUDY AREA

The most remarkable feature of ice-sheet wastage in the study area is the limited occurrence of sand and gravel deposits, these being confined to the NW part of the Carsphairn Lane valley and to isolated forms in the Loch Doon basin. It has been suggested that the former deposits were related to the development of an englacial water-table that was held up between the present watershed and the more coherent ice farther to the SE. The absence elsewhere of extensive fluvio-glacial deposits is believed to be due to rapid dissipation of meltwater (which carved several large meltwater channels in the central part of the main Carsphairn Lane - Water of

Deugh - River Ken valley) along routes now occupied by the present drainage system.

14.6 THE LOCH LOMOND ADVANCE

The extent of 11 former glaciers that developed during the Loch Lomond Stadial has been inferred from terminal and hummocky moraines as well as from the distribution of erratics. The glaciers were almost entirely confined to corrie or trough-head locations where conditions were especially favourable for their accumulation. The influence of direct insolation and the transfer of snow by wind from adjacent high ground have been emphasised as factors that controlled glacier size. It has also been inferred that SW airstreams were important in providing snow during the Loch Lomond Stadial in this area, which accords with inferences made in studies of former glaciers in the Lake District and parts of the Scottish Highlands.

14.7 GLACIAL CHRONOLOGY IN THE WEST-CENTRAL SOUTHERN UPLANDS

In the absence of datable deposits, many unanswered questions necessarily remain concerning the chronology of glaciation in the west-central Southern Uplands. However, the study area contains direct evidence of only two glaciations. The first was in the form of an extensive ice-sheet that submerged even the highest summits. During its retreat, a complex series of landforms composed of till was deposited. Whether or not the ice-sheet finally disappeared from the area before the climatic deterioration that characterised the Loch Lomond Stadial is not known. However, the limited extent of

the Loch Lomond Advance glaciers (9.92 km^2) along with inferred mean July temperatures of ca. 15°C for the area during the Lateglacial Interstadial suggest that total deglaciation occurred.

14.8 SUGGESTIONS FOR FURTHER RESEARCH

- (i) More research is required on the movement of ice in ice-shed situations. Detailed studies of glacial erratics in limited areas may provide valuable data on conditions of former ice flow in these locations.
- (ii) Roundness analysis of glacially transported clasts in ice-shed locations would repay closer attention, for the widely held view that roundness values rapidly increase towards sub-angularity down-ice from the point of entrainment has been found to be untenable in the present study.
- (iii) The valley-fill/cross-valley ridge/drumlin landform association has been shown to have a genetic link. Thus a re-evaluation of, for example, the formation of drumlins and cross-valley ridges may be necessary and attention focused instead on a whole range of landforms.
- (iv) The influence of clast shape on the form of till fabrics, as shown for example by Drake (1974, 1977), requires that future till fabric studies should include evaluation of the size and shape of the measured clasts.
- (v) More extensive use of the distributions of erratics, where circumstances permit, could help delimit former Loch Lomond Advance glaciers where morphological evidence is scanty.

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APPENDIX I: PARTICLE-SIZE ANALYSIS

Olive till (all samples from cross-valley ridges unless indicated)

Sample number	National Grid Reference	% sand	% silt	% clay	*M _z	σ_I	Sk _I	K _G	Sample location
B/3	NX 566929	53.8	39.5	6.9	4.4	2.25	-0.03	0.96	
C	NX 576924	66.8	25.0	8.7	3.73	2.17	-0.05	0.94	
E	NX 553932	36.3	57.2	6.6	4.76	1.88	-0.33	1.29	inter-ridge
F	NX 531956	63.4	27.6	9.1	3.54	2.61	-0.17	0.75	
G	NX 495013	74.5	22.4	3.3	3.38	2.15	-0.11	0.89	drumlinoid
H/2	NX 528965	43.0	45.4	11.8	4.76	2.35	-0.13	0.95	
I	NX 498998	36.0	37.4	26.6	5.14	2.55	-0.03	0.89	drumlin
J/2	NX 528965	55.2	36.2	8.5	4.37	2.53	-0.05	0.77	
K	NX 577825	58.1	30.2	11.0	3.84	2.55	-0.12	0.81	drumlinoid
L	NX 578933	35.8	51.5	12.9	5.26	2.42	-0.16	0.84	inter-ridge
M	NX 571926	59.8	32.7	7.3	3.98	2.11	-0.01	0.92	
N	NX 569929	54.7	33.4	12.0	4.1	2.44	-0.06	0.88	
O	NX 566932	50.4	39.7	10.3	4.76	2.08	-0.02	1.04	valley-fill
P	NX 562933	71.2	23.6	5.0	3.72	2.26	-0.09	0.96	valley-fill
Q	NX 608861	66.5	30.4	3.1	3.8	1.91	-0.12	0.86	drumlin
R	NX 588902	65.1	30.5	4.5	3.73	2.39	-0.07	0.81	
S	NX 594891	63.4	31.1	5.6	3.82	2.31	-0.06	0.81	
T	NX 598885	49.5	33.5	17.2	4.46	2.52	-0.04	0.86	
U	NX 599879	67.6	25.2	7.4	3.41	2.48	-0.23	0.79	
V	NX 651787	33.4	35.3	31.4	4.99	2.66	-0.09	0.83	drumlin
W	NX 615834	56.7	33.6	9.7	4.1	2.5	-0.07	0.79	drumlinoid
Y	NX 576856	59.4	28.7	10.8	4.04	2.56	-0.06	0.84	drumlinoid
Z	NX 587846	57.4	35.1	7.8	4.14	2.79	-0.04	0.67	drumlinoid
A/A	NX 603863	60.8	32.6	6.4	4.16	2.37	-0.09	0.82	
B/B	NX 647858	55.5	31.2	12.9	4.22	2.46	-0.04	0.81	drumlin
E/E	NX 596928	65.8	24.1	9.9	3.57	2.44	-0.2	0.85	
G/G	NX 608907	42.5	48.0	8.5	4.89	2.05	-0.19	1.16	
K/K	NX 657922	71.5	22.3	6.2	3.64	2.00	-0.06	0.98	valley-fill
L/L	NX 648910	55.8	39.8	4.2	4.27	2.14	-0.13	0.87	
M/M	NX 559936	60.5	35.7	5.8	4.22	1.99	-0.03	0.91	
N/N	NX 574925	52.1	38.9	8.6	4.36	2.21	-0.12	0.93	
O/O	NX 576924	68.4	24.9	6.8	3.62	2.29	-0.14	0.87	

Particle-size analysis (continued)

Sample number	National Grid Reference	% sand	% silt	% clay	*M _Z	σ_I	Sk _I	K _G	Sample location
<u>Olive till (continued)</u>									
P/P	NX 576923	61.9	32.5	5.5	4.03	2.04	-0.15	1.04	
Q/Q	NX 577923	57.5	32.4	10.0	4.07	2.67	-0.09	0.72	
R/R	NX 578926	85.7	8.6	5.6	2.53	1.82	-0.29	0.99	
U/U	NX 525929	56.8	28.0	15.2	4.14	2.56	-0.19	0.79	
Y/Y	NX 538962	58.0	30.5	11.5	4.12	2.27	-0.08	0.86	
Z/Z	NX 539961	51.7	31.1	17.5	4.41	2.52	-0.08	0.82	
GW1	NX 562952	56.9	34.1	9.1	4.17	2.79	-0.23	0.79	} valley-fill
GW2	NX 562952	55.0	29.5	15.7	3.29	2.21	-0.29	1.14	
GW4	NX 562952	74.6	16.8	8.7	4.14	2.63	-0.08	0.75	
GW5	NX 562952	59.3	34.2	6.6	3.99	2.4	-0.03	0.79	
A/C	NX 589928	83.3	12.6	4.6	2.94	1.76	-0.08	0.9	
A/D	NX 591922	67.1	28.0	4.6	3.86	2.13	-0.04	0.89	
A/E	NX 592922	54.1	36.4	9.6	4.21	2.69	-0.02	0.75	
A/F	NX 591919	77.4	18.5	4.2	3.39	1.96	-0.11	0.94	
A/G	NX 589901	70.0	22.2	7.8	3.67	2.11	-0.37	0.97	
A/I	NX 629911	57.6	35.5	6.4	4.02	2.32	-0.13	0.84	valley-fill

* Particle-size parameters: M_Z = mean size (ϕ);

σ_I = sorting;

Sk_I = skewness;

K_G = kurtosis.

Particle-size analysis (continued)

Sample number	National Grid Reference	% sand	% silt	% clay	*M _z	σ_I	Sk _I	K _G
<u>Grey till</u>								
H/1	NX 528965	37.2	33.5	29.4	4.98	2.42	-0.02	0.84
J/1	NX 528965	38.8	31.5	29.9	4.95	2.71	-0.04	0.8
F/F	NX 602902	42.3	31.9	25.7	4.69	2.54	-0.04	0.84
H/H	NX 623908	42.2	31.4	26.2	4.67	2.61	-0.04	0.83
I/I	NX 626910	39.6	30.3	30.2	4.79	2.66	-0.02	0.83
J/J	NX 657922	34.4	32.3	32.9	4.87	2.65	-0.09	0.77
S/S	NX 522930	45.0	36.8	18.2	4.75	2.63	-0.01	0.82
T/T	NX 524930	44.7	30.2	24.7	4.64	2.62	-0.09	0.99
V/V	NX 532932	58.4	29.6	12.3	4.02	2.39	-0.07	0.91
W/W	NX 534932	35.3	35.2	29.7	5.22	2.78	-0.03	0.75
X/X	NX 546933	44.5	35.3	20.0	4.75	2.39	-0.12	0.68
GW3	NX 562952	31.9	21.4	46.7	4.75	2.82	-0.13	0.77
A/H	NX 629911	25.8	36.0	38.3	5.52	2.59	-0.19	0.84

* Particle-size parameters: M_z = mean size (ϕ);
 σ_I = sorting;
Sk_I = skewness;
K_G = kurtosis.

APPENDIX II: ROUNDNESS ANALYSIS - 1.25 to 2.0 ϕ size fraction.Olive till (all samples from cross-valley ridges unless indicated)

*Sample number	**VA	A	SA	SR	R	WR	Sample location
B/3	39	48	12	1	-	-	
C	31	50	18	1	-	-	
E	35	48	16	1	-	-	inter-ridge
F	34	50	16	-	-	-	
G	31	55	13	1	-	-	drumlinoid
H/2	34	51	13	2	-	-	
I	28	52	18	2	-	-	
J/2	37	46	14	3	-	-	
K	28	43	25	4	-	-	drumlinoid
L	33	53	12	2	-	-	inter-ridge
M	27	51	20	2	-	-	
N	32	53	12	3	-	-	
O	27	53	17	3	-	-	valley-fill
P	27	55	18	-	-	-	valley-fill
Q	28	57	14	1	-	-	drumlin
R	37	49	14	-	-	-	
S	38	48	14	-	-	-	
T	26	58	16	-	-	-	
U	30	57	12	1	-	-	
V	17	50	30	3	-	-	drumlin
W	24	56	20	-	-	-	drumlinoid
Y	24	56	19	1	-	-	drumlinoid
Z	40	52	8	-	-	-	drumlinoid
A/A	27	54	18	1	-	-	
B/B	25	41	33	1	-	-	drumlin
E/E	29	55	16	-	-	-	
G/G	26	54	17	2	1	-	
K/K	24	54	21	-	1	-	valley-fill
L/L	26	54	19	1	-	-	
M/M	35	47	18	-	-	-	
N/N	38	50	11	1	-	-	
O/O	35	50	15	-	-	-	

Roundness analysis - 1.25 to 2.0 ϕ size fraction (continued)

*Sample number	**VA	A	SA	SR	R	WR	Sample location
P/P	33	51	16	-	-	-	
Q/Q	26	60	13	1	-	-	
R/R	39	47	14	-	-	-	
U/U	37	51	11	1	-	-	
Y/Y	27	58	15	-	-	-	
Z/Z	30	48	19	2	1	-	
GW1	33	56	10	1	-	-	valley-fill
GW2	38	48	11	3	-	-	
GW4	36	46	12	4	2	-	
GW5	31	48	17	4	-	-	
A/C	30	54	15	1	-	-	
A/D	26	58	15	1	-	-	
A/E	29	58	12	1	-	-	
A/F	35	50	15	-	-	-	
A/G	22	63	15	-	-	-	
A/I	35	45	18	2	-	-	valley-fill

* See Appendix I for National Grid references for sample sites.

** Roundness classification after Powers (1953)

VA = very angular; A = angular; SA = sub-angular;

SR = sub-rounded; R = rounded; WR = well rounded.

Roundness analysis - 1.25 to 2.0 ϕ size fraction (continued)Grey till

Sample number	VA	A	SA	SR	R	WR
H/1	25	48	27	2	-	-
J/1	18	42	38	2		
F/F	30	50	18	2	-	-
H/H	13	47	38	2	-	-
I/I	21	52	24	3	-	-
J/J	17	58	25	-	-	-
S/S	32	48	19	1	-	-
T/T	27	44	26	3	-	-
V/V	15	57	26	2	-	-
W/W	16	55	27	2	-	-
X/X	19	51	29	1	-	-
A/H	15	49	35	1	-	-

Roundness analysis (continued) - -4.0 to -8.0 ϕ size fractionOlive till (all samples from cross-valley ridges unless indicated)

Sample number	VA	A	SA	SR	R	WR	Sample location
B/3	35	49	15	1	-	-	
C	43	54	3	-	-	-	
E	18	54	25	2	1	-	inter-ridge
F	36	49	15	-	-	-	
J/2	18	66	16	-	-	-	
L	46	46	7	1	-	-	inter-ridge
M	29	56	15	-	-	-	
N	30	58	12	-	-	-	
O	27	55	17	1	-	-	valley-fill
P	27	63	10	-	-	-	valley-fill
T	35	55	9	1	-	-	
K/K	24	56	20	-	-	-	valley-fill
M/M	37	51	7	3	2	-	
N/N	24	60	16	-	-	-	
O/O	36	54	9	1	-	-	
P/P	49	45	4	2	-	-	
Q/Q	27	59	13	1	-	-	
R/R	41	47	10	2	-	-	
U/U	27	67	6	-	-	-	
Y/Y	22	61	14	3	-	-	
Z/Z	37	51	11	1	-	-	
GW1	33	56	10	1	-	-	valley-fill
GW2	38	48	11	3	-	-	
GW4	36	46	12	4	2	-	
GW5	31	48	17	4	-	-	
A/C	18	65	17	-	-	-	
A/D	22	63	13	2	-	-	
A/F	37	53	6	4	-	-	
A/G	38	49	11	2	-	-	
A/I	36	50	14	-	-	-	valley-fill

Roundness analysis - -4.0 to -8.0 ϕ size fraction (continued)Grey till

Sample number	VA	A	SA	SR	R	WR
J/I	5	36	55	4	-	-
F/F	25	50	25	-	-	-
H/H	15	47	36	2	-	-
I/I	21	52	24	3	-	-
J/J	18	56	26	-	-	-
S/S	44	47	9	-	-	-
T/T	27	44	29	-	-	-
V/V	36	53	9	2	-	-
W/W	27	60	13	-	-	-
X/X	19	50	30	1	-	-
A/H	20	40	39	1	-	-

APPENDIX III: WEATHERED GRANITE DEPOSITS

In the central part of the Loch Doon basin an apparently deeply weathered granite was discovered on the southern flanks of Shiel Rig (NX 464937), 2 km east of Loch Riecawr and at an altitude of 274 m. The deposit was exposed in sections up to 100 m long in a quarry excavated by the Forestry Commission. In various parts of the quarry up to 3.5 m of weathered granite (pale brown; 10YR, 6/3) were exposed. The deposit merged invariably into sound granite bedrock below, while in the weathered parts core stones of coherent granite were well developed (Plates XVII and XVIII). The weathered granite was overlain by a peaty podzol soil averaging 0.4 m in depth. In some sections of the quarry a thin (10 - 30 cm) slope-wash deposit of olive-grey silty clay was present between the weathered granite and soil profile. The surface vegetation comprised wet *Calluna* moor.

The weathered granite generally exhibited either a platy or blocky structure when excavated, but crumbled easily into individual grains in the hand. Under the microscope the aggregates were seen to comprise loosely compacted grains of feldspar, quartz and biotite, the latter in considerable quantities. The individual feldspar grains were usually reddish or pink in colour and showed signs of cracking or fracturing on their crystal faces, but little sign of alteration. Contrastingly, the biotite had a ragged and corroded appearance, was soft and extensively decomposed; the quartz grains were not altered in any way.

Particle-size analysis was carried out on a series of samples



Plate XVII: Corestones in the weathered granite deposit by
Shiel Rig (NX 464937), Loch Doon basin.

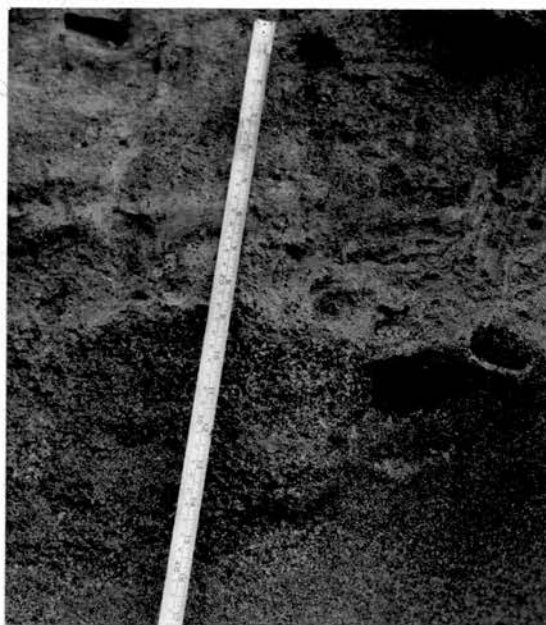


Plate XVIII: Section in the weathered granite by Shiel Rig
showing contact with sound granite.

removed from one section in the quarry and the results are shown in Table III.1. One striking aspect of these results is the low percentage of clay-size material (4.2% to 8.5%). In addition, the higher percentages of the clay- and silt-size fractions appears confined to the upper 1.2 m of the section, they generally decreasing in abundance towards the base.

Table III.1: Results of particle-size analysis on a series of samples recovered from weathered granite deposits by Shiel Rig, Loch Doon basin.

Sample number	Depth from surface - m	% sand	% silt	% clay
1	0.7	64.0	27.5	8.5
2	1.0	80.1	12.8	7.1
3	1.1	77.7	15.9	6.4
4	1.2	67.7	24.8	7.5
5	1.4	89.7	5.8	4.5
6	1.5	94.1	2.0	3.9
7	1.6	91.2	3.9	4.9
8	2.1	88.8	6.2	5.0

The location of the weathered granite is enigmatic. It has been shown in Chapters 5 and 6 that the Loch Doon basin was a major centre of ice accumulation and that the glacial landforms in the area are characteristic of intensive ice erosion. Indeed, hard, polished granite with ice-moulded moutonnée forms occur less than 400 m to the east of the deposit. Similarly the summits of the adjacent Shiel Rig and Shiel Craig show signs of extensive erosion by ice.

The mineralogical and particle-size composition of the Loch Doon weathered granite suggests that it differs from that found in

the humid tropics. Support for this view is found in the studies of weathered granite from these climatic regions. Bakker (1967) found that the weathered granite was characterised by an absence of feldspar and a clay content of up to 55 per cent. Similarly Ruxton and Berry (1957) described weathered granite from Hong Kong that was devoid of feldspar, as did Eden (1971) from Guyana. The Loch Doon deposits seem more to resemble the "sandy weathering type" described by Bakker (1967) from the granitic areas of France and Czechoslovakia or the "granitic grit" of Jahn (1962), these deposits being characterised by the presence of feldspar and a low clay content (less than 7 per cent). Controversy surrounds the climatic environment under which these deposits were considered to have been formed, however; they having been attributed either to a sub-tropical climate (Linton 1955; Bakker 1967) or to the present cool temperate climate (Collier 1961).

Although no direct evidence exists to demonstrate the climatic environment in which the Loch Doon weathered granite was formed, the results obtained suggest that the deposit is not a strongly chemically weathered regolith produced by pedogenetic processes of considerable duration under hot, humid climatic conditions. Its origin is particularly enigmatic, however, when considered in the light of its landscape position both as a small area surrounded by completely unweathered rocks as well as its surviving glacial over-riding when the immediately surrounding area has been strongly glaciated. The presence of deeply weathered soil profiles in areas, from other parts of Scotland, within the limit of the last glaciation have been described by Phemister and Simpson (1949), Linton (1959),

Fitzpatrick (1963), Smith (1963) and Wilson (1967, 1969). In certain of these localities the weathered profile was overlain by periglacial debris (or deposits interpreted as till). As a result, formation of the deposits has been regarded as being due to weathering during warmer inter- or preglacial periods, the deposits having escaped removal by over-riding ice by virtue of their location in apparently "unglaciated enclaves" or beneath ice cap source areas (cf. Boulton 1974).

In view of these interpretations several possibilities exist regarding the origin and preservation of the Loch Doon weathered granite. First, it may be a product of inter- or preglacial weathering that has survived glaciation. Wilson and Bown (1976) have suggested such an origin for the gibbsite-rich soils on the summits of Merrick and the Rhinns of Kells range. Although the deposits described by them lay within the former ice-divide zone described in Chapter 5, the deposits by Shiel Rig are 7 km north of the ice-divide and on the south-facing side of that hill. Thus given the degree of erosion by ice in the area it seems difficult to envisage their survival in such a locality. Secondly, the deposits may be entirely Postglacial in age. Certainly weathering of exposed bedrock during the Postglacial has occurred, for recent road cuts through the dolerite sills by the Forth Road Bridge for example already show signs of weathering. However, this is usually a comparatively thin skin on exposed faces (cf. Hornung and Hatton 1974) and is also due to the susceptibility of these iron-magnesian-rich rocks to weathering processes. In addition, it does not explain the localised nature of the deposits in the Loch Doon basin.

A more likely possibility is the influence of pneumatolytic or hydrothermal alteration of the Loch Doon granite during or after its emplacement. That such phenomena occurred is evidenced by the graphite, haematite, lead and silver mineralisation adjacent to and within the intrusion (e.g. NX 4676; NX 5093; NX 5293). The high percentage of biotite in the weathered granite by Shiel Rig (compared with that observed elsewhere) may have been particularly susceptible to such alteration and that this weakened the structure of the rock in this locality. Eggler *et al.* (1969) studying the granites of Colorado-Wyoming have shown that oxidation of biotite by high temperature fluids during crystallisation led to expansion of the biotite and structural weakening of the rock, which resulted in the rapid disintegration of the granite upon exposure at the surface. Similar conclusions were reached by Kennan (1975) in his study of the weathered granite at Turlough Hill, Co. Wicklow, Eire as well as by Rutherford and Churchward (1975) who analysed a deeply weathered foliated amphibolite in the SE Canadian Shield. In both of the latter studies alteration of the bedrock was considered to be of ancient origin and an important condition in modifying the structure and coherence of the rock.

Thus it is suggested that exposure of the structurally weakened, biotite-rich granite at the surface (by glacial erosion) in the Loch Doon basin has led to selective and extensive weathering of the granite during the Postglacial by the acidic nature of surface waters percolating from the surface peat. Such a conclusion would obviate the need for "special pleading", which would be required if the deposits were regarded as of inter- or preglacial age and had survived removal by over-riding ice on numerous occasions.

USE OF THE CHI-SQUARE TEST FOR THE ANALYSIS OF ORIENTATION DATA¹

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ABSTRACT: The chi-square test has been extensively employed by geologists and geomorphologists as a measure of the strength or statistical significance of preferred trends within orientation data. The χ^2 value obtained is dependent on arbitrary selection of the pattern of sectors into which orientation measurements are grouped. The calculation of all possible χ^2 solutions for 98 sets of 50 stone orientation measurements demonstrated that a wide range of χ^2 values could be calculated for most samples. The hitherto widespread use of the test in this way cannot therefore be considered a valid mode of analysis, and the results of previous studies employing this methodology must be treated with extreme caution. The use of a different test statistic is advocated.

INTRODUCTION

The chi-square test has been used extensively by geologists and geomorphologists for the analysis of orientation data. The test has generally been employed as a measure of the strength or statistical significance of preferred trends within such data. Although it has been used in sedimentological studies of various kinds (e.g., Rusnak, 1957; Caine, 1968a, b; McSaveney, 1971; Statham, 1973), the chi-square test has been particularly favoured for the analysis of the orientation of pebbles within till (e.g., Harrison, 1957; Kauranne, 1960; Kirby, 1961, 1969; Andrews, 1963; Andrews and Smithson, 1966; Harris, 1969; Hill, 1971; Mark, 1971; Reheis, 1975) and its use for the analysis of orientation data has been described in several standard texts (e.g., Chayes, 1949, p. 298; King, 1966, p. 310; Andrews, 1971, p. 30; Doornkamp and King, 1971, p. 348; Norcliffe, 1977, p. 197).

In such studies, sets of n orientation measurements have been grouped into k equal-sized sectors (e.g., 0° to 19° , 20° to 39° , etc) and tested for departure from a uniform distribution of points about a circle. The form of the chi-square equation that has been employed is therefore one in which the expected frequencies in each sector (E) are all equal to n/k , and is given by:

$$\chi^2 = \frac{1}{E} \sum_{i=1}^k (O_i - E)^2$$

where O_i is the number of measurements that fall into each sector. As the expected frequency (E) for each sector must (by statistical convention) exceed 5.0 (Dixon and Massey, 1969, p. 238), the number of sectors employed should not exceed $n/5$. For this reason, the measured frequencies (O_i) in diametrically opposite sectors have often been summed. This permits the technique to be used on smaller samples without the loss in precision that would result from reducing the number of sectors and hence increasing their size.

The principal advantages of the chi-square test for the analysis of orientation data (Cornish, 1979) are that it is easily understood and calculated, and being non-parametric is appropriate for the analysis of non-normal circular distributions with a single dominant mode. The test has certain limitations, however, in that it yields no indication of the distribution of measured orientation values (Pincus, 1953) and may give ambiguous results for distributions that have strong secondary modes.

A further problem concerns the choice of the point of origin from which the pattern of sectors is generated, in that the frequency of measured orientations in any sector (O_i) is liable to change when the point of origin is changed. This note assesses the magnitude

¹ Manuscript received October 16, 1978; revised March 26, 1979.

of possible errors introduced into this form of analysis by arbitrary selection of the point of origin for the pattern of sectors into which measurements are grouped, and discusses possible alternatives.

ANALYSIS

In order to assess the extent to which calculated χ^2 values vary with changes in the pattern of sectors, a FORTRAN IV program was written to compute every possible χ^2 value for 98 sets of orientation data, measured from a variety of glacial and periglacial deposits. Each data set comprises 50 stone orientation measurements; orientation was measured to the nearest 5° for 43 samples, and to the nearest whole degree for the remainder. In order to satisfy the convention of $E \geq 5.0$, the data were grouped in nine sectors of 20° , using summation of frequencies in diametrically opposite sectors as described above. For orientation measurements made to the nearest degree, 20 different groupings of points are possible, and hence up to 20 different χ^2 values may be calculated. For measurements made to the nearest 5° , however, only four (20/5) groupings of points are possible, and up to four different χ^2 values will result.

The ranges of calculated χ^2 values for these samples have been summarised with reference to commonly-used levels of significance (Table 1) and are plotted in rank order on the dispersion diagram shown in Figure 1.

RESULTS AND DISCUSSION

It is immediately apparent from Figure 1 that the range of calculated χ^2 values for any sample is too large to allow any single,

arbitrarily selected χ^2 value to be considered representative. For 30 of the 98 samples, the maximum χ^2 value obtained is over twice as large as the minimum value, while for 73 samples the maximum value is over 1.5 times greater than the minimum value. More importantly, the range of χ^2 values calculated for 62 of the 98 samples transgresses at least one, and often more, of the six commonly-used significance levels shown on Figure 1. This indicates that, for these samples, the level of significance obtained is entirely dependent on the point of origin chosen when the chi-square calculation is carried out. The most extreme differences in significance level were exhibited by the samples ranked as numbers 43 and 48 in Figure 1, which have χ^2 ranges of 11.92 to 30.28 and 10.86 to 28.21 respectively. Depending on the pattern of sectors employed, the χ^2 values obtained for these samples can indicate that the distributions of measured orientations are either not significantly different from a uniform distribution at a low (0.1) level of significance, or that they differ significantly from such a distribution at a very high (0.001) level of significance. Moreover, Table 1 indicates that, for the 98 samples analysed, the 0.05 significance level is very sensitive to ambiguities arising from the arbitrary choice of point of origin, yet tests of preferred orientation have been made more frequently at this level than any other.

When the same analysis was employed using data with $n = 100$ and $k = 18$, equally large ranges of χ^2 values resulted.

Although researchers employing the chi-square test in the analysis of orientation data have rarely indicated the point of origin employed in selecting the sectors into which the data were grouped, it would seem likely that most have used sectors originating at 0° or 1° . However, there is no reason why such groupings should give more representative results than groupings based on, for example, 6° , 12° or 17° . It is clear from the ranges of χ^2 values illustrated in Figure 1 that such arbitrary selection of the point of origin of the sectors may give equally arbitrary results, making tests of significance a meaningless exercise. The hitherto widespread use of a single calculated χ^2 value as a measure of the strength or statistical significance of orientation measurements

TABLE 1.—Summary of the ranges of calculated χ^2 values for all 98 samples with reference to commonly-used levels of significance

Level of Significance	No. of Samples with All χ^2 Values Not Significant	No. of Samples with Range of χ^2 Values Crossing Given Significance Level	No. of Samples with All χ^2 Values Significant
0.1	19	34	45
0.05	23	44	31
0.025	32	40	26
0.01	45	33	20
0.005	50	29	19
0.001	66	15	17

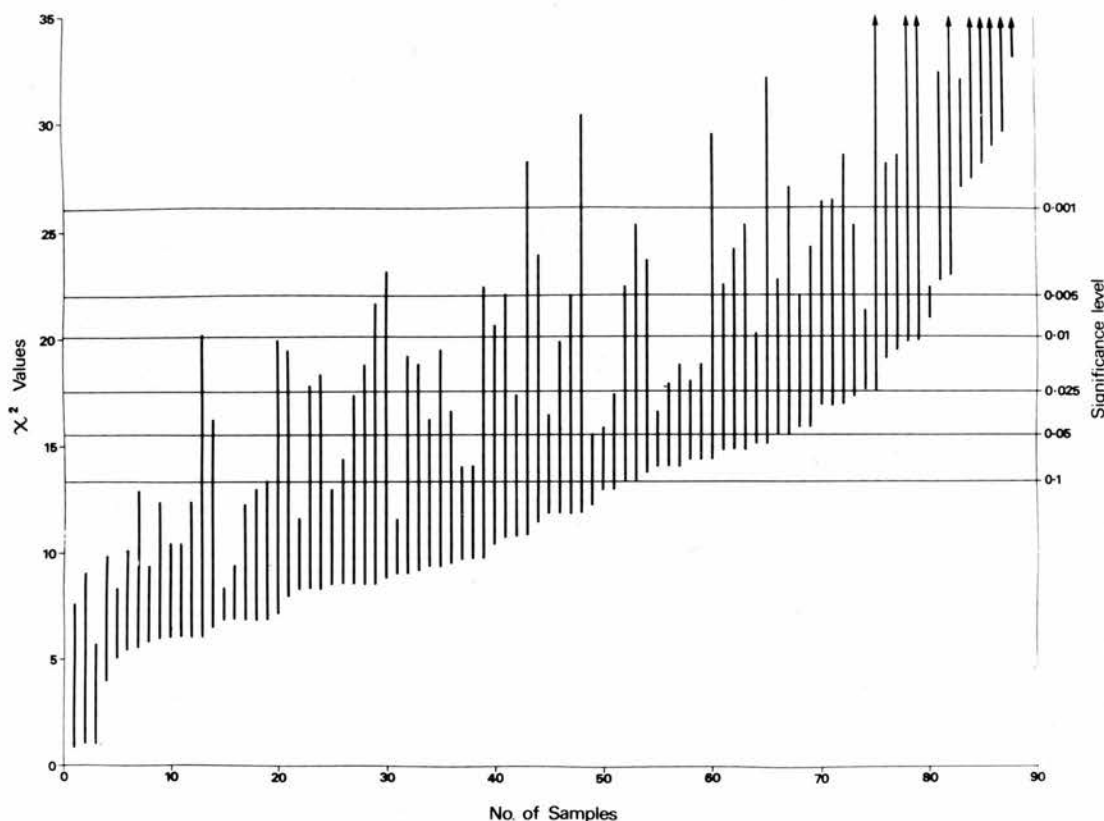


FIG. 1.—The range of possible χ^2 solutions for the orientation data samples employed in the analysis. The vertical lines represent the range for each sample; lines with arrows extend beyond the range of the graph. Ten samples have ranges that fall completely outside the range of the graph and are not shown.

cannot therefore be considered a valid mode of analysis, and the results of previous studies employing this methodology must be treated with extreme caution.

ALTERNATIVES

Several modifications of the chi-square test were investigated in an attempt to devise a more rigorous procedure for assessing the statistical significance of preferred trends in orientation data. The use of extreme values (the maximum and minimum calculated χ^2 values) is unacceptable as (a) exceptionally high (or low) χ^2 values can result from chance groupings of orientation measurements and (b) the probability distribution of the maximum and minimum chi-square statistics are unknown. A more feasible alternative is the selection of some value representative of all possible solutions, such as the mean or median. However, analysis of the form of the

distributions of calculated χ^2 values revealed little regularity; most of the distributions analysed were bimodal, multimodal or skewed. No measure of central tendency can therefore be considered representative of all cases. The only suitable solution would therefore appear to be the use of a different test statistic; several possibilities have been reviewed by Mardia (1972), and one of these, Ajne's A_n statistic, has recently been recommended for use in studies of this type (Dale and Ballantyne, in press).

ACKNOWLEDGMENTS

The authors gratefully acknowledge the expert advice of Dr. M. J. Baxter and S. Dowers on aspects of statistics and computing. M. A. McMillan made available twelve of the samples used in the analysis. Dr. N. Caine and Dr. J. B. Sissons provided useful comments on the manuscript.

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